introduction

In the 2016-18 Three-Year Plan of the CNR, our Department has divided the research activities of its Institutes into 21 Project Areas, in turn classified into 4 Strategic Areas.

This Report collects the white papers of the 21 Project Areas, realized by the researchers of the Department.

The Department's main purpose is to support the research activities of the Institutes, carrying out the following tasks:

1. Coordination between strategic areas and contacts with the external scientific community;
2. Promotion of multidisciplinary and inter-departmental activity providing opportunities for action in contexts where the individual Institute fails to act;
3. Scouting of innovation, analyzing development trends and questioning companies about their research needs and activating groups of institutes/researchers according to the demand;
4. Participation in National Technological Clusters, where possible, by coordinating public research structures (University, Public Research Agencies);
5. Participation of the Department and its institutes as proponents of Knowledge and Innovation Communities (KICs) on strategic issues (e.g. Blue Growth);
6. Participation with a role of inter-ministerial and inter-institutional coordination of national research, innovation and technology transfer efforts;
7. Promotion of research agreements with large multinational companies and international research organizations;
8. Sensitization of research staff towards technology transfer and business creation, strengthening the function of technical support to the Institutes;
9. Support for the management of large-scale projects, avoiding duplication of administrative skills in the Institutes, and increasing the efficiency of the Department/scientific network system;
10. Identification of future scenarios of intervention that take into account new technological trends, new problems and emerging needs, also in light of what countries do where investments in science and technology are greater.
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EXECUTIVE SUMMARY

The Project Area (PA) entitled “Devices and Systems for ICT” is a cross-cutting research area that focuses on the development of a broad range of devices and technologies, encompassing photonics, microwave/millimeter-wave technologies, micro/nano-electronics, and chemical electronics.

The objective of the PA is to make new components and technologies available to ICT applications, including next-generation 5G terrestrial and satellite networks, Internet of Things (IoT), environmental monitoring, diagnosis of civil structures and cultural heritage, Industry 4.0, automotive, nuclear fusion, and healthcare. In this context, the activities are aimed at increasing the Technology Readiness Level (TRL) of the components/systems/processes involved, from the concept and formulation (TRL 1-2) to the experimental verification in the operational environment (TRL 7), through proof-of-concept and bread-boarding (TRL 3-5).

Depending on the specific technology maturity, the activities at CNR are carried out within the framework of programs funded by agencies (European Commission, European Space Agency, Italian Space Agency, Fusion for Energy, MISE, MIUR) for more fundamental researches, and industrial contracts with national companies for industry-driven activities. In this scenario, CNR plays an important role in supporting the national industry by boosting knowledge transfer in fields relevant to many application domains.

The activities carried out in this PA can be clustered in three main topics, i.e. photonics, microwave and millimeter-wave technologies and devices, and micro and nano-electronics technologies.

1. STATE OF THE ART OF THE RELEVANT SCIENTIFIC AREA

**Topic 1 Photonics**

Photonics is one of the most pervasive KETs in ICT and has a major impact in many areas including classical and quantum information and communication, industrial manufacturing and production, life sciences and health-care, environmental and structural health monitoring, smart lighting, energy saving and production, food quality assessment, aerospace, safety and security, cultural heritage.

Optical sensors, classical and quantum light sources (from LEDs to VCELs and QDs), fiber, integrated and micro-optical devices (like micro or nano-resonators), are all examples of key technologies allowing the generation of light and its management through guidance and manipulation, and can apply to all types of societal challenges.

**Sensors**

Optical sensors are emerging to play a vital role in several areas, ranging from environmental monitoring to biomedical diagnostic. The wide range of wavelengths from UV to the Mid-IR now available, thanks to new laser technologies, permits a specific and quantitative analysis of the samples under investigation. The continuous miniaturization of optical components has led to the development of highly integrated optical sensing techniques and devices (from millimeter size gratings to nanotips), including additional functionalities, like microfluidics, and leading to self-contained microsystems and lab-on-chip.

Fiber grating based sensing is a well consolidated research field with application for the structural health monitoring and in all the fields in which low intrinsic invasiveness and immunity from electromagnetic fields are required. This technology is therefore extremely useful and convenient in harsh environments as compared to conventional non-dielectric sensing systems.
Recent developments in the solid-state-laser research area have been triggered by the availability of new host materials like transparent polycrystalline ceramics, because of the possibility to achieve a higher uniformity in the distribution and higher concentrations of dopants.

VCSELs cover 99% of the ICT optical sources, and are used for short range huge volume of data transmission and for a very broad range of sensing applications, ranging from OCT, to popular 3D applications for unmanned car driving or smart phone applications. The VCSEL production volume is exploding and more and more help from CAD-oriented simulation tools is requested.

Self-organized Quantum Dots (QDs) grown by epitaxial techniques offer unique opportunities to realize compact and high-efficiency photon sources for the continuously evolving field of information and communication technologies. Making use of the well-established semiconductor fabrication technology, epitaxial QDs can be integrated on a chip and coupled with waveguides and optical cavities.

**Resonators**

High-Q optical micro-resonators have recently gained great attention due to the possibility of using these devices for both fundamental studies and for practical applications. Beside studies in the field of non-linear optics, opto-mechanics, and quantum optics, several resonator-based devices have been implemented mainly in sensing and RF photonics.

Recent works have demonstrated that nanomechanical resonators can be coherently coupled and manipulated with optical and microwave cavity fields, exploiting peculiar quantum properties to enhance the efficiency of the measurement and/or to integrate the extracted information in quantum communication systems.

**Topic 2 Microwave and Millimeter-Wave Technologies and Devices.**

Antennas and passive assemblies are key building blocks of radio-frequency (RF) systems developed for a broad range of applications, encompassing terrestrial and satellite telecommunication, industrial sensors, automotive radar, Earth and Space observation. In very recent years, the way these devices are developed has started to be revolutionized by digital manufacturing, where parts are built by additive manufacturing processes, most commonly known as 3D-printing. These technologies allow for very high integration and miniaturization of components, thus enabling the implementation of new RF architectures aimed at next-generation 5G terrestrial and satellite networks, RF receivers with very high sensitivity, wearable and smart systems for IoT. Meanwhile, the experimental testing and monitoring of wireless systems have benefit from the use of new technologies, such as Unmanned Aerial Vehicles (UAVs) integrated with Tx and Rx capabilities. Connected to the antenna systems, microwave front-ends working at steadily increasing frequencies (millimeter-wave bands available for 5G connectivity from 24-86 GHz) are analog circuits that necessitate a design approach very different from the low-frequency counterparts due to propagation effects and have to be implemented according to the latest semiconductor technologies developments.

For fusion plasma heating applications, Mega-watt (MW) class Continuous-Wave (CW) gyrotrons are being developed. In plasma heating plants (such as ITER that will be composed of more than 20 gyrotrons and will deliver a combined heating power of 24 MW) dummy loads are essential components and very few commercial models of loads are capable of absorbing and measuring continuous-wave at MW level.

Sensing technologies perform non-invasive characterization of surface and subsurface features of materials or manmade objects thanks to the electromagnetic waves ability to interact with them. Among these, Ground Penetrating Radars (GPRs), working from 1 MHz to 100 GHz, are exploited in several applications and continuous efforts are towards the development of sophisticated data processing approaches. More recent sensing technologies relying on THz waves are currently under development because of higher resolution and material identification capabilities.
**Topic 3 Micro and Nano-Electronics Technologies**

During the last years, sensors have increased more and more their capabilities, thanks to the integration of different functionalities, typical of integrated circuits (ICs), allowing them to reach a level of smartness which goes beyond a simple measure and to be employed for a wider range of applications. Several industrial sectors are exploiting these innovative smart sensors, including automotive, production automation process, robotics and aeronautics. One of the most interesting field, that has a great potential of development in the future, regards human healthcare and wellness, which technology is giving a great contribution for. Nowadays a great effort is spent to the development of a variety of possible methods of integrating and packaging sensor/MEMS and IC components, and the technology of choice strongly depends on the device, the field of application and the commercial requirements.

Magnetic materials are used as active elements in micro-sensors based on fluxgate or Hall type electronic devices in which they act as magnetic flux concentrators. Besides miniaturization and increase of sensitivity, a very important requirement is the direct integration of magnetic materials in Si processing technologies that can enable multiple new functionalities.

Analysis of concentrations of gas components plays a crucial role in several applications, ranging from inspection of exhausted plumes in vehicles to the analysis of breath for assessing physiological parameters and assess health status. To achieve this goal several new technologies have been proposed either based on semiconductor sensors or remote sensing technologies (e.g., differential optical absorption spectrography). Nevertheless, suitable algorithms for data processing are still deserved to analyze the response of such non selective sensors and to properly assess actual gas concentrations.

Both organic and inorganic systems integrating sensors and/or bioelectronic devices with logic architectures, based on memristive technology, are explored to overcome the current limits in biomedical and neurological applications. These devices and systems are also used as key elements for the development of unconventional computing approaches based on neuromorphic systems, such as novel fully hardware perceptrons demonstrating the ability to produce reliable and functional systems for complex tasks, including classifications of data.

### 2. CONTRIBUTION TO THE RELEVANT SCIENTIFIC AREA

**Topic 1 Photonics**

Contact Person: G. Nunzi Conti (g.nunziconti@ifac.cnr.it)

CNR institutes involved in the topic: IEIIT, IFAC, IMEM, IREA

**Sensors**

**Subtopic 1.1 and subtopic 1.3 Optofluidic and Fiber optics distributed Sensors**

Contact: R. Bernini (bernini.r@irea.cnr.it)

The activity of IREA is focused in the design, development and characterization of new sensing strategies and techniques that permits to push to limits of the performances of optical sensors. In particular hollow core and optofluidic waveguides able to confine in the same place the light used for sensing and the sample (liquid or gas) under analysis have been developed. These waveguides has been used in order to realize integrated optical devices like microresonator or enhanced spectroscopic techniques (UV, Raman). Novel fabrication techniques based on polymeric materials have been implemented in order to realize high performance and low cost disposable optical sensors. IREA is also involved in the development of distributed fiber optical sensor for physical and chemical measurements over large distances.
Subtopic 1.4 Fiber gratings.
Contact: Cosimo Trono (c.trono@ifac.cnr.it)

The main activities regard the project and development of advanced sensing systems based on fiber grating (Bragg gratings, FBG, and long period gratings, LPG) and fiber lasers. The possibility of realizing custom prototypes adapted and optimized for the particular application, makes IFAC a prominent actor in this field.

Subtopic 1.5 Silica nanotips.
Contact: Stefano Pelli (s.pelli@ifac.cnr.it).

A new technique to fabricate silica nanotips has been developed at IFAC and has been patented. The method is based on a special chemical etching process that can be applied to standard silica fiber and results in tips having controllable sizes down to 40 nm. These devices can be used in high spatial resolution intracellular sensing platforms as well as for studies in plasmonics and non-linear optics.

Sources

Subtopic 1.2 Vertical cavity surface emitting lasers (VCSEL).
Contact: Pierluigi Debernardi (pierluigi.debernardi@ieiit.cnr.it)

Given the unavailability of an adequate multiphysics VCSEL commercial simulations tool, IEII T is developing an in-house software which can handle the optical, thermal, electric transport and optical gain interrelated problems.

Subtopic 1.7 High power blue LED for biomedical applications.
Contact: Roberto Pini (r.pini@ifac.cnr.it.)

High power blue LED based devices has been designed and optimized up to the maximum TRL level targeting the treatment of wounds. Indeed, the system has been proven in operational environment demonstrating that blue LED sources can induce a photothermal effect to immediately stop the bleeding of a superficial wound.

Subtopic 1.8 Development of innovative diode-pumped solid-state-laser based on transparent ceramics emitting in the IR and VIS regions.
Contact: Angela Pirri (a.pirri@ifac.cnr.it).

Our research has focused on the fabrication and characterization of gain ceramic materials doped with several trivalent rare-earth ions as Yb, Dy,Er, which allow emitting in the IR and VIS regions. Our work has contributed to clarify the influence on the laser behavior and performances of different spectroscopic and microstructural characteristics of the transparent ceramics we investigated.

Subtopic 1.9 Quantum Dot nanostructures for photon emission at telecom wavelengths.
Contact: Paola Frigeri (paola.frigeri@imem.cnr.it).

To address the need of efficient, bright and integrable light sources for laser applications and single-photon devices, we study the design and the preparation by Molecular Beam Epitaxy (MBE) of InAs/GaAs and metamorphic InAs/In(Ga)As Quantum Dot (QD) nanostructures grown on GaAs substrates.

We perform model simulations, photoluminescence (PL) and structural characterization of the MBE-grown nanostructures aimed to tune QD emission wavelength in the 1320 – 1550 nm telecom window and to improve QD optical light-emission properties. The accurate control of the experimental growth conditions allows obtaining in-plane QD densities low enough to enable single-dot characterization and processing.
**Resonators**

**Subtopic 1.6 High-Q optical micro-resonators.**
Contact: Gualtiero Nunzi Conti (g.nunziconti@ifac.cnr.it).

The activities include the design, fabrication, and characterization of high quality-factor (Q) optical micro-resonators based on whispering galley modes. More specifically resonators made in crystalline fluorides with ultralow losses and very broad transparency windows are used into innovative low noise optoelectronic oscillators. Similarly, silica based microbubble resonators are used as innovative transducers in photoacoustic microscopy and for label free biochemical sensors.

**Subtopic 1.10 Micro/nano optomechanical oscillators with low optical and mechanical loss.**
Contact: Michele Bonaldi (mbonaldi@fbk.eu).

One of the major obstacle to the realization of exploitable sensors is the extreme delicacy of quantum effects that can be destroyed by thermal noise. In fact, all quantum effects observed to date have been obtained on resonators placed in a cryogenic environment. We are progressing toward a new generation of optomechanical systems, able to maintain a quantum behavior even at room temperature. For this purpose, we are developing devices with low optical and mechanical losses, based on innovative designs and optical metamaterials.

**Topic 2 Microwave and Millimeter-Wave Technologies and Devices.**
Contact Person: O. A. Peverini (oscar.peverini@ieiit.cnr.it)

**CNR institutes involved in the topic:** IEIIT, IREA, IFP

**Subtopic 2.1 Microwave and millimeter-wave passive systems and antennas.**
Contact persons: G. Virone (giuseppe.virone@ieiit.cnr.it)

In this area, CNR is involved in the development of novel architectures of multi-beam antenna systems working form 50 MHz to 110 GHz aimed at HTS (High Throughput Satellite) communication platforms with Terabits aggregate capacity, Earth Observation (EO) instruments with high spatial resolution for next-generation MetOP-SG and Copernicus sentinels, radio-astronomy and astrophysical instrumentation. The outdoor experimental characterization of complex and large antenna arrays, such as Italian and European demonstrators of the Square Kilometer Array, is successfully tackled by integrating Tx sources in UAVs.

**Subtopic 2.2 Active Circuits for Wireless-Communication Systems.**
Contact persons: R. P. Paganelli (rudi.paganelli@ieiit.cnr.it)

This topic deals with investigation, modelling, design and realization of both integrated and hybrid circuits for RadioFrequency (RF) front-ends: power and low noise amplifiers, programmable phase shifter and attenuators, switching power converters, oscillators and mixers. The research is evoted to improve the best trade-off among the most important figure of merit as linearity, efficiency, dynamic range, bandwidth, sensitivity, long term stability and reliability. Various wireless power transfer (WPT) methods are also included in this topic.

**Subtopic 2.3 RF Technologies for Nuclear Fusion Research.**
Contact persons: A. Simonetto (simonetto@ifp.cnr.it) e A.Bruschi (bruschi@ifp.cnr.it)

CNR has developed a unique dummy load concept designed for 2 MW CW that, while more expensive than commercial alternatives, has shown outstanding performance in tests on different test-stands worldwide and can be easily scaled to future multi-MW CW plants.
Subtopic 2.4 Electromagnetic Diagnostics Systems and Technologies.
Contact Person: Ilaria Catapano (catapano.i@irea.cnr.it)
CNR has assessed skills regarding electromagnetic modelling of forward and inverse scattering problems as well as development and performance assessment of methodologies and technologies for acquisition, processing and interpretation of GPR and THz data. In particular, application oriented data-processing strategies, which are based on a proper modelling of the interaction among electromagnetic waves (microwave and THz) and materials, have been developed and exploited widely in different applicative contexts ranging from subsoil investigations, to security and diagnosis of civil structures and cultural heritage. These strategies usually combine noise-filtering procedures with approaches facing the imaging as an inverse scattering problem and allow accurate, reliable and easily interpretable images of the probed scenarios by properly managing large amount of data.

Topic 3 Micro and Nano-Electronics Technologies
Contact Person: F. Albertini (franca.albertini@imem.cnr.it)
CNR institutes involved in the topic: ISTI, IMEM, IEIIT

Subtopic 3.1 Hardware/Software Platforms for Gas Analysis
Contact Person: Davide Moroni (davide.moroni@isti.cnr.it)
The activity aims at designing and developing gas sensor-based platforms for gas analysis. In combination with robust and optimized methods of signal processing, the concentrations of the target volatile molecules can be assessed. Recently, a portable device for human breath analysis has been developed; it is based on an array of commercial, semiconductor gas sensors and a signal acquisition board. It is able to detect, in human breath, specific volatile compounds related to cardiometabolic risk.

Subtopic 3.2 Si-Integrated Magnetic and Magneto-Optical Sensors and Devices.
Contact Person: F. Albertini (franca.albertini@imem.cnr.it)
This activity aims at Si-integrated magnetic and magneto-optical materials and technologies for the production of current/magnetic field sensors, biosensors, magnetic MEMS, integrated inductors: preparation and characterization of materials and devices and technological transfer.

Subtopic 3.3 Electronic and electrochemical devices for sensing, radiation detection, unconventional computing and bioelectronics.
Contact Person: Victor Erokhin (victor.erokhin@fis.unipr.it)
Development of electrochemical devices (Organic Electrochemical Transistors (OECTs)) with customized performance and architectures, fabricated on Si and flexible substrates, for sensing, monitoring of systems activity (Lab on Chip configuration) and neuromorphic applications, prepared through different micro-scale technological processes and innovative features:

- 3D-OECTs fabricated by Additive Manufacturing (patent pending) to increase the Limit of Detection
- OECTs with nanometric channels for fast, miniaturized devices
- OECTs with functionalized graphene-based electrodes to improve selectivity towards specific analytes
- OECTs with nanostructured active layer based on electrospun nanofibers for enhancing transducer/analyte interaction.

Development of memristive organic-based devices and logic circuits for the implementation of:

- 1 and 2 perceptrons
- Systems integrating sensing and memristive devices for the local sorting of as-collected signals.
Subtopic 3.4 MEMS and Smart Sensors based on Thermal Principles and Micro/Nano-Structured Materials

Contact Person: Lucanos Strambini (lucanos.strambini@ieiit.cnr.it)

In the framework of smart sensors the activities performed at CNR concern the design, fabrication and experimental characterization of micro-nanosensor/MEMS integrated on the same chip with the electronic interface necessary for signal acquisition and processing. Micro and nano-structuring of silicon and the employment of new materials (i.e. polymer) are the key elements involved for the development of a new class of devices with improved sense capabilities and integration potentialities with IC components. To this purpose both standard IC technology and silicon/polymer based new fabrication process techniques (i.e. porous silicon technology) are involved. Some results of such activities concern the design, fabrication and characterization of MEMS-based microsystems (e.g. thermal flow sensors, solid-state anemometers, acoustical sensors) porous silicon-based sensors for gas sensing and biosensing applications, and polymer-based transducers for the field of flexible devices. As parallel activity, the design and implementation of electronic interfaces, from both hardware and software point of view, are performed to connect (biasing and communication) such smart devices with the outside world.

3. IMPACT

Topic 1. Photonics

Sensors

The possibility to perform high performance measurements at low cost through optofluidic and fiber optics distributed sensors could represent a paradigm shift from snapshot measurements to continuous monitoring. This pervasive sensing could address current social challenges from environmental pollutions up to global healthcare.

The capability of implementing custom sensors (based for instance on fiber gratings and nanotips) can be strategic for specific applications in which commercial sensing systems cannot be employed.

Sources

By overcoming several simulation challenges in terms of models, accuracy and simulation speed a significant impact is expected in the exploding production volumes of VCSEL, which are becoming a pervasive and enabling technology.

The improvement of the fabrication techniques will enhance the optical quality of the ceramic material and improve the laser performances by obtaining shorter laser pulses and higher intensity sources.

The development of compact and integrable Quantum Dot (QD)-based photon sources with high quantum efficiency aims to explore novel solutions in nanophotonic science with technological breakthroughs in the fields of communications and information processing. These findings will impact on the future well-being and secure data communication. The tailoring of the light-emission properties of self-organized semiconductor QDs, performed by means of the material and growth design, represents one of the first fundamental steps of this technological evolution.

Resonators

Ultra-high Q optical micro-resonators are key components for the development of ultra-compact stable frequency combs for high-precision metrology and spectroscopy as well as for quantum communications. Single molecule detection in biomedical applications and ultra-broadband photoacoustic microscopy are targeted with hollow silica based micro-resonators.

An optomechanical platforms operating at the quantum level could be integrated both within existing “classical” networks and devices, and within the future quantum networks able to process quantum signals and information. This achievement will be relevant also to the much broader scenario of the MEMS and
sensor industry which, as a fundamental technological player, is boosting the development of the Internet of Things for a more connected world.

**Topic 2 Microwave and Millimeter-Wave Technologies and Devices.**

Microwave and millimeter-wave antenna systems have a key role in the development of next-generation 5G networks of mobile internet connectivity, offering faster speeds and more reliable connections on smartphones and other devices than ever before. Digital divide between geographic areas will be reduced by integrating terrestrial and HTS communication systems.

At the same time, dense antenna focal planes allows for EO instruments with the sensitivity levels needed in climate-change monitoring missions (MetOP-SG, Copernicus) and cosmology studies. Finally, RF sensors for industrial applications can increase working safety conditions, such as in steel casting industry, where RF sensors can replace radiative sources that are commonly used for monitoring the level of the molten metal liquid.

RF front-end electronic circuits are particularly affected by the technologies advances in the field of semiconductor fabrication and assembly. Therefore, the impact of these circuits is high in many applications where their use is consolidated, while they can become enabling technologies for future applications not yet practical at present.

A successful production of a suitable dummy load is a necessary condition for the development of new gyrotrons, essential for ITER and for other present and future devices in which the fusion plasmas are heated with microwaves, as foreseen in future demonstrative (DEMO) and commercial fusion power reactors.

Microwave and THz systems (hardware device plus data processing) capable of performing non-invasive surveys are demanded in all those applications where is required to gather information about surface and subsurface features of a certain object and thus represent a possible technological solution for many open issues traced into national and international research programs.

**Topic 3 Micro and Nano-Electronics Technologies**

Automation for home and automotive applications, Internet of Things (IoT), Industry 4.0, Augmented and Virtual Reality (AR/VR), Artificial Intelligence (AI) are emerging/pervading Information and Communication Technologies (ICTs) with high impact at scientific, industrial, social and political level. All these technologies are strongly demanding of small devices that are able to integrate into a “simple element” the capabilities of computing, communication and monitoring systems. In this framework, the activities on sensor/MEMS and IC components integration and new silicon/polymer technology could have a high impact making available very small, low power, low cost and smart devices for several current emerging ICTs, with applications in the environmental monitoring as well as sensing and biosensing areas.

Hardware/software platforms for gas analysis can be exploited in multiple cases of use: from the monitoring of environmental gases to the investigation of human breath composition. The activity may also include the development and the characterization of ad-hoc gas sensors (i.e. polyaniline nanofiber – based gas sensors highly sensitive to specific odorants, such as cigarette smoke, present in human breath) in collaboration with other research centers.

The developments of contactless magnetic sensors and devices and their integration with Si-technologies can have a strong impact in several crucial field of application, including electrical mobility, consumer electronics and nano-medicine.

The short-term perspectives for OECT are focused on the accumulation of a robust and diversified technological experience in the fabrication of OECTs devices, through the combination of several advanced technological tools. In the medium-to-long term, OECTs will be customized with different structural properties and features to optimize the response with respect to specific application scenarios and to widen the portfolio of potential application fields.
4. EMERGING RESEARCH CHALLENGES

Specific research challenges for photonics devices and systems includes:

- Solving the complexity of implementing software for VCSELs design which requires multidisciplinary approaches, validations with experiments, and parameter fittings.
- Fabrication and characterization of transparent ceramics with emission in the VIS regions.
- Optimization of the emission efficiency and operating temperature of QD-based photon sources and integration of QD nanostructures with optical components at nm-scale to develop a complete on-chip quantum nanophotonic circuit.
- Controlling resonator dispersion to push the combs into the visible

Challenges are planned to be tackled by participating at research programmes, some of them already identified, focused on the relevant fields in conjunction with both research institutes/academy and industrial partners. The PA researchers are also participating in agencies and networks committees, so as to contribute to the roadmaps and harmonization dossiers (as the ones coordinated by ESA and ASI for the GSTP, ARTES, TRP, H2020 programmes) that will define the activities to be implemented in the incoming future, among which are,

- Digital manufacturing of microwave/millimeter-wave products.
- Flexible electromagnetic monitoring and testing through UAV-based RF systems.
- Active circuits implemented with the latest device technologies (GaN, pHEMT, mHEMT).
- Gyrotrons with dummy loads at powers up to a few MW (2 or more) in CW.
- GPR systems exploiting new observation platforms (UAVs).
- Consolidation of THz imaging systems.
- Polyaniline nanofiber, magneto-optical, Si-Integrated magnetic, and nanoelectronic sensors.
- Interfacing human and brain signaling for optimized, direct control of devices, prosthesis and health status.

5. CONCLUSIONS

The PA “Devices and Systems for ICT” is cross-cutting by nature, allowing for the technological development of ICT products to be used in many applications. As a consequence, the PA proves to be the cornerstone for several activities to be carried out in other PA’s, such as Earth Observation based on radiometric imaging, cultural heritage monitoring, healthcare, and internet of the future, just to mention a few.

The PA is well established at CNR level within the strategic area entitled “System and Telecommunication Engineering”, and at national and international level within the framework of several research programs and industrial contracts.

The competences of the researchers involved cover a wide spectrum of topics, from photonics to micro/nano-electronics, through millimeter-wave technologies. This interdisciplinary nature is an added value for the successful development of new ICT products, based on the implementation of concurrent-engineering methodologies.

The man-power effort and known-how of the CNR staff involved and the research facilities are relevant, thus guaranteeing a significant CNR impact in the research area. In this scenario, an adequate turn-over of the personnel would be beneficial so as not to lose the competences and the capabilities to manage advanced research laboratories.
EXECUTIVE SUMMARY

Future Internet activities have a number of innovative and impacting trends in industries and society and are influencing topics such as knowledge distillation from big data, social networking, secure systems, digital industry. Many recent and emerging paradigms are related to our activities, to mention a few Cyber Physical Systems (CPS), Internet of Things (IoT), Internet of People (IoP). Further information may be found in vision documents and strategic agenda such as Artemis-IA, HiPEAC, EPoSS and others.

Looking at the national and international context in the next 5-10 years, it is possible to cluster our activities in three themes, i.e., Next Generation Internet (NGI), Distributed Parallel and High Performance Computing (HPC), and Software Engineering (SW). The NGI theme covers communications, network monitoring, novel Internet paradigms, and IoT technologies, with a special emphasis on Industrial Internet (Industry 4.0). HPC deals with cloud, edge computing and high-performance computing. SW covers all typical aspects of software engineering, including formal methods, software monitoring, testing and verification, programming paradigms such as agent-based models.

We are perfectly aligned with the Future Internet strategic research directions, at the national and international levels. With respect to FP9 [FP9], two of the three themes (NGI and HPC) are “Areas of Intervention” for the “Digital and Industry” cluster under the “Global Challenges and Industrial Competitiveness” pillar. SW will not be a specific Area of Intervention, but it is indicated in many others (e.g., “Digital Technologies” and NGI), as a key enabling theme. All activities are relevant also in the other FP9 pillars, i.e., “Frontier” (covering infrastructures and ERC), and “Open Innovation”. The three themes are present in the research agendas of the main non EU funding agencies. For example, they are subject of NSF solicitations in the Computer Systems Research (CSR) [CNS17] and the Cyber-Human Systems (CHS) [IIS17] areas.

This characterization also maps into the latest Italian PNR program [PNR15]. The three themes are relevant for the five “bacini di domanda” and the 12 “aree di specializzazione”. Results from the DIITET activities are applicable to all the four considered technological groups: “Prioritarie” (Fabbrica Intelligente), “In Transizione – Emergenti” (Smart Communities, Tecnologie per ambienti di vita), “Ad alto potenziale” (Made in Italy), “Consolidate” (Mobilità).

1. STATE OF THE ART OF THE RELEVANT SCIENTIFIC AREA

1.1 Theme: Next Generation Internet

NGI encompasses the FP9 areas [FP9] of Future Internet communication and networking. The SoA can be described for key lines in the NGI research agenda.

NGI communication technologies beyond 5G and network measurements

Communication systems have a range of applications, i.e., health-care, smart-living, manufacturing. New microcontroller and radio technologies have also enabled new products. Considering the exponential number of radio devices [VF14], wireless networks are dense, calling for self-organized and cognitive architectures [SSSB08].

Mobility aspects (mobile Internet) at different scales, from pedestrian to vehicular, are key. With vehicles autonomously communicating, mobile technologies become critical to support novel services [EU17]. Satellites and UAVs (Unmanned Aerial Vehicles) are part of the (beyond-)5G technologies, complementing global coverage of terrestrial communications.
Finally, measurements techniques characterise the current Internet and NGI. New methodologies for large-scale NGI topological maps are required.

**NGI network paradigms**

NGI is human-centric [FP9]: users are immersed in personal mobile devices and “things” generating data. Personal devices become “proxies” of their users and adopt models of the human behavior to organize the network and filter data. This vision is a root of NGI [FP9], and already generated a research community [CDP17,L18,Q16,B17].

NGI is also a Information-centric (or data-centric) [XVS16]. ICN is expanding from the Internet core to the edges, supporting mobile networks and IoT [ACQ16, BMH14], even though solutions are not yet well suited for them [LAS16, ACM14, GAM14, WK16, BCO14].

Another area is the integration between networking and computation (see Section 2.2).

**IoT and WSN in NGI and NGI industrial networks**

IoT and wireless sensor networks (WSN) are key in many applications, e.g., smart city, smart industry, smart maritime environments. Issues are energy management, QoS, security, data collection, limited resources, robustness. Interoperability is a main pillars [WMRD11], addressing reusable designs for composition of services [DLD16, D18].

In the industrial domain, Industry 4.0 and PNI4.0 [MISE18] trends consider IoT and WSN key technologies [SADSF16]. Issues include decentralization, self-configuration, communication and computing architectures. Data management is key, involving decentralised solutions for data ownership and efficient use of IoT resources.

1.2 **Theme: Distributed Parallel and High Performance Computing**

Two main “technology pushes” shape the landscape of distributed and high performance computing of future Internet: virtualization and many cores version of Moore law. Virtualization drives the transformation of the infrastructure towards cloud, fog or edge. The Moore law, with the end of Dennard scale (2005), provides an increase in the number of cores rather than of the clock frequency, and parallelism is now a must.

Cloud Computing relies upon large-scale datacenters with thousands of servers, providing pervasive and complex ecosystems composed of many heterogeneous entities (from business intelligence to IoT) that interact and adapt their behaviour to changing requirements [VB18]. This increases the importance of: resource optimization and power savings [GC18, CT17, DCMW17, BCT16]; security preventing data leakage while providing QoS [CM17, SCS17, QCD16]. At the same time is necessary to improve the methodologies for services design [D&al18, MSEJB16, ANE13].

Multi-access Edge Computing (MEC) is a pillar of next 5G solutions in the areas of IoT and mobile networks [SA16], with strong industrial commitments [OC17, TSM17]. MEC applications include content distribution [LXW17], computation offloading, data preprocessing [NRS17], service migration [KCA15], resource sharing. MEC is a key component in the H2020 5G-PPP and is broadly investigated in the literature [PB17]. Hot topics includes offloading at extremely short time scales, virtualization techniques, optimization models and heuristics [TLG16, DLL16], lightweight orchestration [LAM17, SLL16].

High Performance Computing. Efficient and scalable solutions for analyzing big data are among the most urgent research challenges. Machine Learning (ML) and Artificial Intelligence (AI) can nowadays model complex phenomena by relying on the exploitation of huge training datasets through HPC techniques [ABC16]. Deep Neural Networks (DNNs) accuracy depends on hyper-parameters whose setting require to run massive jobs. Open research challenges include the decentralization/parallelization of learning processes to address efficiency and scalability issues [MBY16] and the efficient deployment of complex models in scenarios characterized by near real-time constraints [DLN16]. Other HPC applications in the field of multimedia processing and simulation need to adaptively exploit heterogeneous resources, accelerators and low-power CPUs [Z17, D&al17, D&al14].
1.3 Theme: Software Engineering

SW systems, such as the SW components of Cyber Physical Systems, are made up of computational elements that work together to control entities of various nature and provide services and innovative applications. They are spatially-distributed, time-sensitive, and multi-scale networked embedded systems, connecting the physical to the cyber world through sensors and actuators. They should ensure reliable behaviour even in unpredictable conditions being also user friendly. These new paradigms sparked novel systems and entire research areas such as autonomous driving, industry 4.0, smart cities, or IoT [EG16]. The goals in this context are, e.g., increasing reliability and safety, reducing resource consumption, improving the performance of processes and usability.

The use of a good SW development process and of support tools is essential to guarantee the development of applications and services that respect the aforementioned requirements. Frameworks for automated Business Process (BP) modelling and analysis are becoming a key technological component in support of BP Management and the continuous growth in complexity and pervasiveness of SW systems calls for the use of modern requirements analysis and formal verification techniques, which may play a key role for guaranteeing the correctness of the systems.

SW systems raise the need to integrate several heterogeneous components and environments into corporate-wide computing systems, and to extend their working boundaries beyond companies into the Internet. The IBM manifesto of autonomic computing [KC03] suggests a promising direction for facing software complexity through self-adaptation, that is the ability to automatically assemble ad-hoc functionality as a response to environment changes or when the user changes requirements [CLG09,LGM13].

Finally, according to Gartner [GAR], there will be nearly 26 billion devices on IoT by 2020. It becomes important that users can configure smart environments consisting of thousands of interconnected devices, which will enable many possible interactions in a user’s surroundings. There has been increasing interest in using trigger-action rules for supporting EUD of IoT applications at the commercial (e.g. Tasker [DIN], IFTTT[IFT]) and research level, but trigger-action rule-based approaches can be difficult for non-programmer users because they could raise ambiguity in their interpretation.

2. CONTRIBUTION TO THE RELEVANT SCIENTIFIC AREA

1 Theme: Next Generation Internet

NGI communication technologies beyond 5G and network measurements

Design and optimization of 5G MIMO (IEIIT): analysis of 5G (and beyond) systems and their optimization; new algorithms related to the physical and access level of wireless networks; “conventional topics” such as information encoding, signal reconstruction and channel characterization; “emerging topics” such as massive MIMO, cooperative and cognitive systems [CSNZ13] and ultra-low power designs; energy-efficient transmissions for industrial wireless networks [ASS17, SRS14]; optical coherent communications [TBF17]; information-theoretic characterization of the limit performance of systems, optimization of communication protocols and energy resources.

Design and optimization of mobile and vehicular networks (IEIIT): new architectures for vehicle-to-vehicle and vehicle-to-infrastructure communications [BZM16,BMZC16] using full-duplexing to increase capacity and reliability [BCM18] [BMZ17]; analysis of the space-time dynamics of the demands for mobile services in urban areas [FFS17]; models and predictors of such demands, for data-driven management of (beyond-)5G networks; mobile edge computing and network slicing [NMS18]; models based on large-scale real-world datasets [MGF17], also for population density estimation and land use detection [FFSZS17].

Satellites and UAV communications (ISTI): we are coordinating the TIM 5G experimentation in the sites of Bari and Matera in scenarios where UAVs are used. We consider four scenarios, using drones: 1) public safety; 2) radiofrequency jammer detection; 3) monitoring of the electromagnetic field; 4) precision agriculture.
Network measurements (IIT): crowd-sourcing techniques to measure the Internet graph via distributed approaches. We involve users on a voluntary basis, overcoming dependencies from operators, and allowing to map up to the Internet edge [GGI17,GIL15].

NGI network paradigms

IoP - Internet of People (IIT): IoP is a novel human- and data-centric network paradigm for NGI. DIITET activities include: data collection, using human behavioural models to filter data in mobile edge networks [CMP13, CMPR13, MVCP16, M15, MPC17]; data dissemination, using human social networking models for data dissemination in mobile networks [ACPD17, ALPC16, BCP10, BP10, BCP08, BCP08b].

ICN – Information centric Networking (IIT): solutions for data management compliant with standard ICN architectures for IoT. Our solutions exploit mobile devices forming mobile edge network to provide data-centric access to IoT data [BBP18, BBP16a, BBP16b].

IoT and WSN in NGI and NGI industrial networks

IoT and WSN in NGI (ISTI, IIT, IMATI): WSNs for monitoring purposes in naval, home/office, industry and ambient environments for health and wellness, energy consumption, environmental pollution, sleep quality, logistics, cultural heritage; integration of WSN readings in middleware platforms. Network solutions to provide ultra-reliable IoT communications [ABC14]. Measurement of link qualities with minimal overhead and energy waste [AVBM17]. Scalable and reliable transport protocols for IoT [AVBM17, ABVM18]. Resource allocation in shared sensor networks [BB18].

Industrial IoT (IIT, IEIIT): fixed, wireless cloud-assisted networks, related to both the "core" and "fog/edge" functions [KRSS18]; information processing, network organization, reliable and real time communications, synchronization and management; distributed architectures and algorithms for dense wireless cloud network platforms [SNSS17], including environmental recognition and vision capabilities in IoT working at high-frequencies and wide bands [SSM16]. Distributed data management in industrial IoT, investigating where and when the data should be moved [RP17, ERS18], the role of nodes for data management [RPC18b], network (re-)configuration for optimal data delivery [RPC18].

2 Theme: Distributed Parallel and High Performance Computing

Cloud Computing. (IMATI, INM, ISTI, ICAR) The AP studies optimization techniques for modern datacenters to increase utilization, reduce power consumption, and guarantee security and QoS. We develop optimal placement and consolidation policies using suitable modeling, control, and multi-objective optimization techniques [GC18, GC16b, GC16, GC14]. Workloads of large datacenters are analyzed to devise self-adaptive models able to reduce energy use by keeping the desired QoS [CT17, BCT16QD17, QCD16]. A scalable platform for the combined exploitation of Cloud, mobile and IoT devices is proposed that supports dynamicity and provides location-aware brokering functionalities [ACC+17] [SJS+17].

Edge Computing. (IIT, IMATI, ISTI) We focus on the delegation approach, particularly effective for augmented reality or digital image/video processing [ACM17]. We propose a solution where edge nodes in an SDN-enabled network offer remote execution of elementary computation blocks, providing optimal allocation of incoming requests and monitoring functionalities for the edge servers covering a given physical area.

High Performance Computing (IIT, IMATI, ISTI, ICAR) We target AI and ML algorithms for extremely large datasets by investigating: the reduction of the size of training sets through an intelligent selection of examples [LNP18]; the pruning of ML models to make them compact and fast [LNO18]; evolutionary approaches to optimize DNNs hyperparameters. The efficient deployment of AI/ML models is addressed by dealing with low-level features of modern hardware [LNO15, DLN16, DLN16b]. We address the problem of learning from distributed datasets by considering scenarios where data cannot be moved due to privacy concerns and dynamic settings where nodes and data availability change over time [VPC16, VPC16b, VPC17, VPC17b]. We investigate cognitive models for IoT where devices learn and understand the physical world and can take autonomous decisions as a response to environmental and requirement changes. Finally, we
study parallel algorithms and methods for compute-intensive tasks, such as image processing or simulation, run on heterogeneous architectures including low-power processors for edge computing scenarios [GDC15, MCRSD17].

3 Theme: Software Engineering

The following sub-themes characterize DIITET activities in this area.

Formal Engineering of Cyber-Physical Systems (ISTI)

The main focus of this activity is on the specification, design, analysis, and verification of the behaviours of CPSs in order to prevent failures and malfunctioning. The development of novel software system design processes is supported by requirement analysis techniques [FDEGG17], automatic formal methods [MFS18], stochastic model-based approaches [MCD17]. When analysing a system’s behaviour on the fly/stochastic/statistical/spatio-temporal model checking approaches [BDG17] [CLM18] [BVW17] have been employed.

End user development of internet of things applications (ISTI)

Methods and tools are developed that allow end users without programming experience to customize the context-dependent behaviour of their IoT applications and surrounding appliances and devices through the specification of trigger-action rules. The resulting set of tools is able to support the dynamic creation and execution of personalized application versions more suitable for users’ needs in specific contexts of use [GMPS17].

Agents and self-adaptive systems (ICAR)

The Middleware for User-driven Self-Adaptation framework is setting up for dynamically changing system behaviours, according to the current state of the world, the injected goals and the available capabilities. This is an automatic approach to autonomously taking decisions about how to operationalise a given set of goals. The resulting system exhibits strong adaptation features that consist of a software system that can orchestrate existing functionalities as a response to environmental and user requirements changes.

Testing of software systems and services (ISTI, IASI)

Innovative functional and non-functional testing methodologies as well as comprehensive testing approaches for software system-of-systems focused on the selection, prioritization and orchestration to support test case generation and execution are investigated to validate complex functional and/or non-functional properties of applications built from modular and distributed paradigms.

Monitoring and analysis of software architecture and Smart Environment (ISTI)

Model based specification of business process for verification and validation of functional and non-functional properties as well as monitoring and analysis of software architectures easily adaptable to the IoT environments are developed [BCFM18].

Software Verification via Constraint Solving (IASI)

We develop techniques and tools based on Constrained Horn Clause (CHC) solvers [DFPP-17]. These include transformation techniques to automatically generate CHC formalizations of software properties, and to improve the effectiveness of CHC solvers. We are developing a semantics-based verification approach agnostic with respect to the programming language and the properties to be verified.

Modelling and Verification of Business Processes (IASI)

We pursue a logic-based approach to the modelling of very rich process knowledge, including its procedural behaviour, time constraints, data-dependent manipulations, and ontology-related (OWL) knowledge [DFMPP-17]. The goal is to enable automated reasoning on various aspects of the model by using tools developed in the area of Automated Theorem Proving, such as SMT solvers, Constraint solvers, and DL reasoners.
3. IMPACT

Future Internet activities are at the heart of digital society and of its transformations. The technologies exploited in these activities rely on an Electronic and Component Systems (ECS) Industry that continues to be strong at the European level and still maintains a good participation of Italian companies. Future Internet contributes to mashup ECS technologies into Cyber Physical System, Ubiquitous Computing, Internet of Things, Internet of People and other developments. The applications of the Future Internet are pervasive and pertain a lot of different fields ranging from Industry 4.0, to Well Being, Health Care systems, Secure Society, Energy and others.

Europe is one of the main players in the digital society activities and business. To keep a tight link with European efforts, projects and research agenda are fundamental requirements for Italian research bodies and companies to provide effective impact both from an economic and social point of view.

The advent of the digital society is providing opportunities and threats for the future employment possibilities. While a comment on threats is outside the scope of this document, it is worthwhile to mention that there is a huge request at European level of specialized persons, able to work in Future Internet activities, while there is a significant shortage of these figures. Together with Universities, the CNR labs involved in the Future Internet activities provide top level possibilities to educate and train new professionals. The participation of CNR labs involved in the AP to many national and international projects (see the Appendix) aimed to research, innovation and applications permits to provide unique opportunities to young people. We think that this is a fundamental impact of our activities.

An in-deep quantitative analysis of the scientific impact of our activities is beyond the scope of this report. However, we may put in evidence some qualitative aspects. In most cases, the research groups publish their results in highest quality technical journals (belonging to Q1 and Q2 of the reference sectors) and highly selective conferences. At the same time researchers participate to editorial boards of high impact journals and programme committees of top-level conferences. In addition, they are involved in Expert groups of key EU bodies (e.g., in the area of 5G), and participants to the AP are included in top-level international rankings (such as those of Clarivate Analytics). To keep these scientific capabilities is of paramount importance. The CNR groups working in the Future Internet AP have been able to sustain the quality of their research in the field, despite the increasing difficulties of operating in the research environment, particularly at the national level.

Looking at the active and recently concluded projects in the area carried out by our labs, we get an understanding of the scientific impact of the groups working in the AP. We may notice that impact addresses a wide range of fields, as documented by short project descriptions that the reader may find in the annexes. In some cases, the impact is concerned with enabling technologies such as 5G or Distributed Software design or Cloud thus having a broad range of applications. In other cases, the impact is more focused on a specific target area such as cultural heritage, disaster risk reduction or disposal management, to mention a few. In both cases however the results are quite close to an effective possible exploitation e.g. in an industrial project, or in a new product or service.

At the same time all the scientific and technological activities indicated in the previous Sections provide impact results in different and sometime complementary application areas. It may be of interest to try some classifications of impact of our activities.

We may look at impacts using a per-theme view. We refer to the three main themes listed in the previous Sections, that is NGI, SwEng, and HPC but we also adopt a fourth class “All” for the cases when a mix of the three competences have been exploited. A possible metric is the amount of financial support that the different groups were able to collect considering the last five years of activity. At this regard, we have the following situation: NGI activities collected funds in excess of 2.250 KEuro, SwEng collected more than 660 KEuro, HPC more than 2.380 KEuro and “All” more than 1.325 KEuro. However, this is just a rough measures of effective impact. As an example, one may consider the relevance of SwEng activities that play a very important role at national and international level in the field of rail signalling system. In this case, the SwEng methodologies studied and developed by this AP are of paramount importance to get the desired confidence level in the software development process required by safety figures necessary in railway transportation.
Continuing the per theme analysis we may point out some hot topics. In FP9, the NGI theme will cover both the area of 5G communications and beyond, and the area of Future Internet technologies and paradigms. DIITET is very well placed in both communities. In 5G, in addition to be part of current projects in the area, it is present in the expert groups of Networld 2020, the reference ETP for 5G. In future network paradigms, it is at the forefront of human-centric Internet design, which is one of the key feature of NGI since its conception by the DG CONNECT Director General Roberto Viola. From this standpoint, it is worth mentioning that IIT and IEIIT are supporting, with DIITET agreement, the only proposal for an ESFRI infrastructure in the area of Future Internet, called SILECS, currently under evaluation. In particular, IIT is member of the proposal steering board. For HPC, we expect that edge computing will be increasing its relevance for what concerns architectural aspects, while Machine Learning and similar will play a central role for algorithms. The efficiency and effectiveness of produced solutions will strongly depend on the capacity of exploiting parallel heterogeneous computing systems including low power computing devices.

A complementary view that we may adopt is based on a per-application area classification. A list of area of impacts for our researches and projects include: Energy, both for what concerns its production and its efficient use; Environment, including Disaster risk reduction and waste management; Transport, including railway systems, info mobility and intelligent mobility; Industry 4.0 and leisure industry. With respect to NGI, the DIITET activities are creating impact on all the verticals defined for 5G (https://5g-ppp.eu/white-papers/), i.e., automotive, health, transport, Factories of the Future, Energy and Media. For further information the reader may refer to Annexes of this document.

4. EMERGING RESEARCH CHALLENGES

**NGI.** **Communication:** beyond 5G technologies, air interfaces and radio solutions; minimizing CAPEX/OPEX of satellite networks. **Networking:** human-centric network and data management, pervasive data-centric access. **WSN and IoT:** energy consumption, security, integration of heterogeneous technologies, dynamic configuration, particularly in Industry 4.0.

**HPC.** Cloud asks continuous management of services security, safety and energy issues. Edge asks flexible cooperation of devices with adaptive behaviour. HPC requires portably parallel algorithms for demanding tasks. Solutions embracing the cloud, edge and HPC is an open problem.

**SWEng.** As long as SW grows in size, complexity, heterogeneity and interconnection, it becomes central it to be versatile, flexible, resilient and robust. Novel SW technologies, approaches for reconfiguration, and scalable formal model-based analysis techniques will increase development productivity preserving the SW quality, safety, security and reliability.

5. CONCLUSIONS

This white paper provides a comprehensive summary of the DIITET activities in the area of Future Internet. Future Internet is one of the key “Areas of Intervention” in the EU research agenda (FP9), and is well present in the research agendas abroad, starting from NSF solicitations. In both cases, Future Internet topics are allocated specific funding and objectives, as it is considered an area of active research, in all its dimensions. With respect to the national environment, Future Internet topics permeate the objectives and priorities of the latest PNR, even though it is primarily designed with a vertical application approach, differently from what happens in EU and USA.

The area of Future Internet is clustered around three themes, namely (i) Next Generation Internet, (ii) HPC, and (iii) Software Engineering. This comes from a detailed analysis of the coming FP9 programmes, where themes (i) and (ii) have dedicated areas of intervention, while theme (iii) cuts across several other areas. This classification also maps very well the DIITET contributions in the AP. With respect to NGI, DIITET activities focus on (i) communication issues beyond 5G and network monitoring, (ii) novel NGI network paradigms, and (iii) IoT, sensor networks and industrial Internet. In the area of HPC, DIITET is active in (i) cloud computing, (ii) edge computing, and (iii) high-performance computing. Finally, in the area of software engineering DIITET
contributes to research on all the phases of the typical SW engineering process, including formal methods, software monitoring and testing, as well as novel programming paradigms. Significant interactions across the themes is present. A notable example is the area of IoT, which spans across all the three themes with specific activities.

It is worth noting that DIITET is having a significant impact in the area of Future Internet, mobilising 56.24 FTEs spread across 7 Institutes, with funded project amounting to around 6.6 MEuro.
EXECUTIVE SUMMARY

Smartphones, smart buildings, smart factories, smart cities, autonomous vehicles, and other smart environments and devices such as 2D and 3D acquisition systems, are filled with digital sensors, all of them creating an abundance of data. Governments and health-care entities collect, generate, and use data in an unprecedented quantity. This availability of a huge amount of data, has pushed various disciplines and technologies towards cooperation with the aim of devising ever better models, methods, and algorithms for data acquisition, processing, analysis, visualization, and interpretation.

In this context, the research activities carried-on in the AP “Data, Content, and Media” contribute both to advance methods and technologies and to discover piece of knowledge for a better understanding of individual and collective phenomena and behaviors and for the construction of intelligent and autonomous systems in challenging domains.

The main research and development challenges concern: the modelling, analysis, and visualization of data that cannot be processed with traditional methods (Big Data); the extraction of knowledge and learning predictive models from multi-dimensional, multi-sources, networked, and dynamic data based on artificial intelligence, data mining and network science methods; the intelligent processing of image, audio, and audio-visual content for the development of applications based on content recognition; the intelligent processing of image, audio, and audio-visual content for the development of applications based on content recognition; the analysis and comparison of digital content for 3D models, and more generally, multi-dimensional representations; the development of applied ontologies of socio-technical systems and semantic technologies for their treatment based on the languages of the semantic web (Linked Data) and for semantic interoperability; the natural interaction with computer systems based on multimodal paradigms that make it accessible and usable.

The main research topics addressed by the AP include database and semantic web technologies, knowledge representation and management, data visualization, data mining and pattern recognition, machine learning, and artificial intelligence, complex system theory and network science, information retrieval and text mining, statistics and applied mathematics, natural language processing, computer vision and computer graphics, user modelling and cognitive computing.

The AP research and development activities involves 15 CNR Institutes (CNR-ISTI, CNR-IMATI, CNR-ITC, CNR-IIT, CNR-ISTC, CNR-IREA, CNR-IEIIT, CNR-ICAR, CNR-IASI, CNR-IAC, CNR-ITIA, CNR-IFAC, CNR-IGI, CNR-IRC, CNR-ISTEC), for a total of around 600 person-months per year.

1. STATE OF THE ART OF THE RELEVANT SCIENTIFIC AREA

Digital technology is ubiquitous and very much part of public and private organizations and of individuals’ lives. People and things are becoming increasingly interconnected. Smartphones, smart buildings, smart factories, smart cities, autonomous vehicles and other smart environments and devices are filled with digital sensors, all of them creating an abundance of data including both visual data (2D images, 2D and 3D videos, 3D data) and multimodal and multidimensional signals from environmental and personal monitoring systems. The consequence is the need for methods to extract high-level information from data, including techniques for feature extraction, shape description, matching, classification, and segmentation.

Knowledge Extraction and Semantic enrichment have become a key semantic technology that allows us to produce structured knowledge from unstructured or semi-structured sources. Although basic Natural Language Processing tasks (e.g., word sense disambiguation, named entity recognition) have been configured for Semantic Web tasks (including ontology learning, linked data population), the problem of extracting knowledge is still only partly solved. Being able to automatically and quickly produce quality linked data and
ontologies from an accurate and reasonably complete analysis of unstructured contents would be a breakthrough: it would enable the development of applications that automatically produce machine-readable information from Web content as soon as it is edited and published by generic Web users.

**Big Data analytics**, at the convergence of data mining, machine learning, statistical modelling, and complex systems science, is capable to transparently monitor the quality of data and results of analytical processes. The complexity of machine-learnt models and their widespread use requires novel algorithmic solutions, aimed at rendering fast and scalable both the learning phase and the use of the learnt models in large-scale applications and aspects, such as distributed and cooperative learning, security, and resilience. The training process of both supervised and unsupervised models needs to cope with huge training datasets and latency constraints needed to keep the prediction models fresh and updated. To facilitate and optimize Big Data infrastructures, novel methods need to investigate for distributed indexing, processing, and management, thus going beyond textual compression and including heterogeneous, highly dynamic and semantically-enriched data. Other important aspects are the use of formalisms for explicitly representing knowledge, in order to reason about that knowledge, to make inferences, and to assert new knowledge.

**Data mining algorithms** for automated pattern discovery highlight the structure hidden in massive data sets, such as the clusters of consumers with similar behavior emerging from large user bases, or the modules of proteins with similar functions emerging from the biological networks of protein-to-protein interactions. **Machine learning** - including “deep learning” - methods exploit large “training” datasets of examples to learn general rules and models to classify data and predict outcomes (e.g., classify a taxpayer as fraudulent, a consumer as loyal, a patient as affected by a specific disease, an image as representing a specific object, a post on a social media as expressing a positive emotion).

**Neural networks** and deep learning methods, and more specifically deep convolutional neural networks have recently become state-of-the-art approaches for many computer vision tasks, such as image classification, image retrieval object detection, and object recognition. We expect artificial intelligence and neural networks, in particular, to guide the innovation in Multimedia Information Retrieval and Computer Vision for the next 10 years. Thus, there is a need for further research in artificial intelligence on these specific topics. The most significant open issues are: adversarial machine learning, large scale deep learning, relational learning, multimodal learning, and cross-media learning.

**Network science** has unveiled the magic of shifting from the statistics of populations to the statistics of interlinked entities, connected by the ties of their mutual interactions; this change of perspective reveals the universal patterns underlying complex social, economic, technological and biological systems, and is beginning to understand the dynamics of how opinions, epidemics, or innovations spread in our society, as well as the mechanisms behind complex systemic diseases, such as cancer and metabolic disorders and to reveal hidden relationships between them.

**Visual and multidimensional data, and multimedia** (e.g., images, 3D models, 2D and 3D videos, cartographic digital maps) are among the most popular and pervasive information and communication media, with applications to education, engineering, geographic information systems, bio-medicine, bioinformatics, art, advertisement, entertainment, gaming, cultural heritage, and many others. The increasing interest on multimedia and multi-dimensional data processing and visualization is due to emerging applications, to the proliferation of multimedia devices, and to the huge impact of audio and visual information on daily life. For instance, augmented and virtual reality technologies are becoming widespread and crucial in several fields such as industry, maintenance, health, training, rehabilitation, and leisure. **Geo-referenced** (i.e., associated with a geolocation on the Earth surface or implicitly expressed by place names, points of interest) devices and data are of great importance to develop location-based services for the most diverse fields, such as urban monitoring and planning, tourism and environmental and social sciences. The resulting generation of high-quality data has boosted research in color image processing, image and 3D data analysis, perceptual image evaluation and 3D visualization, spatiotemporal techniques, such as denoising, enhancement, segmentation, and compression methods, specifically defined for processing the input video as a 3D data with emphasis on motion estimation and analysis.
Visual data and media are typically stored as collections and archives of visual, multidimensional, heterogeneous data, and multimedia, which need methods and tools to navigate these catalogues on the web and facilities for searching, browsing, clustering, interacting, and visualizing different kinds of visual data and related information (e.g., geo information) and to automatically extract features able to describe (semantic) contents of the visual/textual data and to effectively/efficiently query the archives, by flexibly considering different granularities and scales, objectives, and regions of interest. Important aspects are the development of best practices for the management of heterogeneous data; e.g., metadata for the input data (e.g., identification, aggregation, versioning, annotation, authorization, embargo), their formats, and the processes applied to data (e.g., for archiving of workflow descriptions, archiving of descriptions of services involved in workflows, archiving of code involved in workflows).

2. CONTRIBUTION TO THE RELEVANT SCIENTIFIC AREA

3.1.1 DATA

Line1: Big data Sensing and Management

The common situation with Big Data is that information come from several data sources of different nature, form (e.g., structured, unstructured) and quality level, resulting in heterogeneous data flows that are difficult to integrate. Major contributes focus on methods for analytical crawling, crowdsensing and crowdsourcing for sensing data from social media and mobile devices, object detection and recognition for sensing data from smart camera networks; for compressing, indexing, and managing massive big data;(e.g., RTI images, images, videos, 3D models).

Line2: Knowledge Representation, Reasoning and Engineering

Knowledge representation goes hand in hand with automated reasoning because one of the main purposes of explicitly representing knowledge is to be able to reason about that knowledge, to make inferences, assert new knowledge, clearly an inference engine as part of the system.

- **Semantics Web Technologies and Languages** such as OWL 2 and RDFS, have been extended with Fuzzy Logic and corresponding reasoning tools (Fuzzy OWL 2 and fuzzyDL).
- **Conceptual modelling and Ontology engineering** developed within several domains including: cultural heritage, natural language, health, software security, public administration, smart cities, agriculture manufacturing, domotics, maritime.
- **Semantic Database** through a valid reference architecture for an RDF store that plays the role of backbone to support large-scale semantic applications, with multiple users.
- **Semantic Search and Retrieval** enabled by ontology-based similarity and relatedness mechanisms.

Line3: Knowledge Extraction and Semantic enrichment

Knowledge Extraction has become a key semantic technology that allows us to produce structured knowledge from unstructured or semi-structured sources). Objects to be enriched range from short posts published on online social network (e.g., texts, tags, pictures, video and audio files) to spatiotemporal data (georeferenced by the GPS receiver of the user) recording the movement of an object in time and space.

- **Entity linking** aimed at identifying in texts the mentions referring to concepts or entities (e.g., Dexter (http://www.dxtr.it/).
- **Linked Open Data**, design and development of linked data, semantic technologies, metadata models, together with standardization efforts (e.g., W3C, RDA), which provide the tools for maximizing interoperability between services, such as data catalogs, e-infrastructures, e-Government settings, and virtual research environments. (e.g., Framester - Linguistic Linked Data Hub).
Semantic enrichment of movement data: pure movement data are enriched with multiple heterogeneous contextual aspects extracted from heterogeneous sources and interconnected by different relations.

Semantic analysis and management of 3D and multi-dimensional data: and more generally, of web resources exposed following the Linked Data paradigm.

CONTENT

Line 4: Data Mining and Machine Learning

The focus is on novel data mining and supervised/unsupervised learning algorithms and their application to specific forms of data, such text, images, multimedia, spatial, temporal, spatiotemporal, graph in order to extract accurate models to rank results of queries, predict the evolution of complex phenomena, classify data items, provide personalized and context-aware recommendations in online and mobile environments, and understand human behavior. The models are the basic break of intelligent autonomous systems for ambient assisted living, autonomous driving, predictive maintenance, and personal driver assistant.

- Foundations and algorithms for data mining and machine learning: pattern discovery, rule generation, motif discovery, clustering (time series, transactional, co-evolutionary), statistical learning, decision trees, convolutional neural networks, reinforcement learning, adversarial learning, causal inference, anomaly/intrusion.
- Text and Sentiment Mining: classifying the generated content (UGC – e.g., a tweet, a product review, a post on a social networking service) according to the sentiment it conveys (or opinion it expresses) about a certain entity, also in multilingual and multi-domain scenarios.
- Mobility Data Mining: a stack of spatial, and spatiotemporal algorithms from basic one as trajectory pattern mining, flocks and clustering to richer one as future location prediction, mobility profile discovery, activity recognition, transfer learning among different territories, functional area detection.
- Neural Networks for Question-Answering: neural networks-based information retrieval and paragraph ranking methods capable to better identify text paragraph candidate to contain the answer to a given question; new text encoding methods and neural network architectures and models having better performances in extracting entities and text passages that constitutes the answer to a given question.
- Large Scale Data Mining and Machine Learning based on Intelligent sampling and pruning methods, mapping learning on CPU’s characteristics with a novel bit-vector representation of tree-based models, model reduction in case of multiscale parameter distributed systems. Applications are mainly focused on the analysis and/or modelling of combustion engines instabilities, flames dynamics and fronts dynamics in forest fires by making use of IR images and/or GIS data.

Line 5: Network Analysis

A world in a continuous evolution requires methods and framework capable of sensing the complexity of the relationships of individuals and adapting at the changes of the evolutionary patterns and models.

- Foundation and algorithms for social network analysis models for dynamic and multilayer networks, link prediction, methods for community discovery, models for information diffusion and epidemics spreading, novel topological measures and predictive models.
- Online Social Networks analysis focused on characterizing the properties that ego networks exhibit in Online Social Networks and on understanding how these properties impact on important processes such as trust and information diffusion.
Line 6: Behavior Analysis

- **Behavior analytics** aimed at predicting what kind of event will take place at what time in the future. Who are the innovators, the leaders? On the base of information diffusion, hidden factors of influence propagation on the base of personal experience to the aim of improving user experience within a specific situation by understanding the patterns governing the user’s choices.

- **(Visual) Cognitive Computing** delivers personalized guidance systems, in particular Virtual Personal Assistants through user profiling to model behavioral and psychological data underlying a successful interaction with the users, adaptive coaching content and message delivery strategies, and user engagement through a rich and unobtrusive user experience.

- **Social Media Analysis**: How does people discuss on online social networks? Who are online social network users that take part in political debate? What is the structure of their social network? What topics are discussed on online debates? Is content fake? The aim is to study how opinions form and spread on line and detect fake news and fake users.

- **Profiling and personalization**: at the base of any form of automatic recommendation and suggestion represent a fundamental tool to characterize user’s interest and habits with the ingestion and analysis of users generated huge amounts of contents.

MEDIA

Line 7. Acquisition, modelling, and analysis of images, videos, 3D and multidimensional data

- **Algorithms and tools for the acquisition, and modelling of images, videos, static and time-varying 3D data** (e.g., complex scenes, deformable/articulated objects from 3D and 4D scans), which are typically acquired by multiple and/or low-cost acquisition devices with different resolutions and applied to virtual/extended reality, engineering (e.g., retrofit and regeneration interventions of the built environment), security (e.g., video surveillance), digital restoration of archive material (e.g., digital copies of prints, photographs, books, movies) using human perception rules, robotics and bio-medicine, biometrics (e.g., iris tracking), health (e.g., rehabilitation, smart ageing, assistive technologies).

- **Algorithms and tools for processing and analysis of 3D data**, where the main research activities and challenges range from the study of representation methods and of geometric analysis tools for 3D shape acquisition and fabrication, modelling, classification and recognition, to knowledge formalization about the shape and the context where it is embedded and used. Specific research activities include the combination of heterogeneous data properties (e.g., shape, color, 2D textures, measured material properties) for patterns’ and features’ recognition, user-driven data exploration and similarity assessment, data indexing and learning.

- **Deep Learning for Multimedia and multimodal Information Retrieval and Analysis**: to analyze images in real time to perform recognition and classification tasks with very high performance and produce high quality interpretations of their content and to perform a broader and contextual analysis of the scene leveraging on the recognized objects/persons/actions and using knowledge based and databases to infer and interpret the scene as a whole.

Line 8. Multimodal Interaction and Accessibility

- **Multi-Modal Interfaces design**: methods and tools to support user interface designers, software developers, and end users in obtaining systems that can be accessed from different contexts of use (devices, users, physical and social environments) in such a way to improve usability, accessibility, and user experience to provide most suitable and natural way of interaction also using wearable and specialized devices. In particular, the work focuses on Adaptive Interfaces, Interfaces for Ubiquitous Applications, MultiModal Interfaces (involving gestures, voice, graphic, vibrotactile-feedback, eye tracking, virtual and augmented reality, brain signal, etc), Tools for Accessibility validation, Usability Evaluation and Models for HCI.
3. IMPACT

**Impact on research**

Open Science paradigm

Previous research activities provide a solid framework to handle many different data sources, ranging from traditional structured data to multimedia data, social networks and spatiotemporal data. Many methods and datasets are made available in conformity with the Open Science paradigm, fostering science advance by means of cross-fertilizing collaborations of researchers, data scientists and practitioners, creating a heterogeneous ecosystem to create new vision on data and knowledge discovery.

Transfer and weakly supervised learning

In those situations where supervised datasets are difficult to collect, we envisage the extension of current learning methods to transfer rules and models learned in a context to other novel scenarios with similar characteristics. Weakly supervised and self-supervised learning are also mandatory in order to leverage on the enormous amount of multimedia information nowadays available on the web and on social media in particular. Finally, another important aspect is the development of scalable methods and algorithms for reducing the time required to train and operate machine learning and deep learning solutions.

3D Data management and visualization

Fundamental research in computer graphics, geometry processing (e.g., MeshLab tool), massive 3D data compression and distribution, and multiresolution efficient rendering, web-based visualization of multimedia data (3DHOP platform & Visual Media Service), 3D fabrication technologies for small-scale series production, computational design of objects based on customizable materials, drone-based 2D/3D sampling, and HDR and RTI images.

Knowledge management form visual and multi media

Extraction and representation of knowledge from text, images, audio, video, 3D data, such as visual attributes or keywords, in a seamless and transparent way to the user. The final aim is to support data and semantic enrichment methodologies and mechanisms to add, complete, and verify data, through quality requirements, users’ feedbacks (e.g., in geo-information) and user reliability. Main platforms include the MIDB system (http://arm.mi.imati.cnr.it/midb) and the VISIONAIR System (http://visionair.ge.imati.cnr.it/).

**Impact on society**

The development of pervasive and distributed intelligent systems can unlock the potential of the data that is routinely collected by cameras and other sensors, with a wide impact on several sectors, such as:

- **support to policy making**, novel ways of producing high-quality and high-precision statistical information, empower policy makers with the means to gain a better understanding of complex socio-economic systems;
- **modern cities** are the perfect example of environments that are densely traversed by large data flows (user-generated including networked smart cameras): urban planning, public transportation, reduction of energy consumption, ecological sustainability, safety and management of mass events;
- **environmental and structure monitoring**, for automatic inspection of areas e.g. by the use of swarm of drones or of other autonomous vehicles;
- **data ethics and privacy** enhancing technologies: the development of complex analytical processes is intertwined with the responsibility of their impact on personal privacy violation;
- **understanding societal debates**. Social online debate, public opinion and issue mapping solutions help organizations understand the people and patterns behind the topics that matter to them most;
• **improvement of accessibility and inclusion.** Innovative HCI methods (gesture/touch/voice/speech recognition, eye tracking, virtual and augmented reality, brain signal, etc.) to provide most suitable and natural way of interaction also using wearable and specialized devices.

**Impact on industry**

**Web-companies:** the capability of managing, searching, and extracting information from visual and social media information and multimedia material on a very large scale, is a strategic competence that has applications in many fields ranging from security to news production, from marketing analysis to edutainment.

**Manufacturing and production:** with industry’s growing investments into Industry 4.0 and smart factories with sensor-equipped machinery that is both intelligent and networked (Internet of Things, Cyber-Physical Systems), the production sectors in 2020 will be one of the major producers of (real-time) data. 3D fabrication technologies have an important impact on industry and the handcraft market. Italy has possibly the most respected design community worldwide, with “made in Italy” products known for their quality, functionality and elegance. Still, Italy is not as competitive as overseas economies in the large-scale manufacturing of products. 3D digital fabrication techniques are bound to change all of that, shifting the manufacturing landscape from the production of many copies of identical objects to a market for unique, personalized designs.

**Sport and gaming industry:** the striking proliferation of sensing technologies and IoT in sports have attracted the attention of the scientific community. In this context, the combination of powerful analytics, visual data and multimedia with new interactive technologies, is transforming many sports: soccer, tennis, biking, etc. are increasingly using data analytics to support training, tactical and strategic game planning (injury prediction, performance evaluation, etc). Gaming industry is pushed by the development of augmented and virtual environments that with higher visual fidelity is resulting in less physical drawbacks, and supports a more pleasant experience and a more effective stimulation, with a faster acquisition of new skills, a save of time and costs (e.g., in the field of rehabilitation from chronic pathologies).

**Material design for fabrication and 3D printing**

While printing hardware is evolving rapidly, design software is not taking advantage of these new capabilities. One of the challenges is the design of surfaces with patterns of predictable appearance and mechanical properties. Scalable algorithms and open source software to accomplish the design task would largely impact on manufacturing, since the inherent advantages of 3D printing hardware, and in particular the ability to mix materials at a sub-millimeter scale, would then be available to designers.

**Visual and sensors’ data analysis and understanding**

Development of new methods for the analysis and understanding of visual data (2D images, MRI images, and 3D data) based on concepts from geometry processing, computational topology and geometry, shape analysis. The methods include techniques for MRI image segmentation and morphological analysis of 3D faces and humans, to find landmarks, facial correlates of cardio-metabolic risk factors. Geometrical and topological methods are also used to analyze time-series of multimodal signals from environmental sensor monitoring, for example to monitor human occupancy in smart buildings.

4. **EMERGING RESEARCH CHALLENGES**

Main challenges are

• a decentralized user centric model for personal data based on block chain and digital identity, where individuals track, recollect, and provide access to their own data to external actors only on request for specific tasks;
the explainability/accountability of Machine Learning Models to support automated decision, guarantee the reliability of ML methods against training bias, and embed ethical values into autonomous systems;

the protection of digital citizens from misinformation in on-line debates, through semantic dissonance detection between headlines and contents in published news, integration of effective fact-checking methods from knowledge bases/crowdsourcing;

the development of interactive systems that are mobile and interactive, support additional senses (voice, gestures, virtual/augmented visualization, vibrotactile-feedback, eye tracking), have a higher accuracy and quality experiences, incorporate bio or environmental sensors.

5. CONCLUSIONS

Smartphones, smart buildings, smart factories, smart cities, autonomous vehicles, 2D and 3D acquisition systems and other smart environments and devices are filled with digital sensors, all of them creating an abundance of data (e.g., images, 3D models, 2D and 3D videos, cartographic digital maps). Governments and health-care entities collect, generate and use data in an unprecedented quantity. This availability of a huge amount of data, has pushed various disciplines and technologies towards cooperation with the aim of devising ever better models, methods, and algorithms for data processing, analysis, visualization, and interpretation. Such technologies are a significant component of what is meant by Artificial Intelligence nowadays.

In this context, the research activities carried-on in the AP “Data Content and Media” contribute to advancing the methods and technologies for data, content, and media (i.e., from data acquisition, to data modelling, representation, analysis, query, and visualization) and to discovering piece of knowledge needed to build intelligent and autonomous systems in challenging domains.

These activities are made possible by the involvement of extremely different skills: database technology and semantic technologies, data mining, machine learning and artificial intelligence, data visualization, computer vision and computer graphics, complex system theory and network science, statistics and statistical physics, information retrieval and text mining, natural language processing, computer science, applied mathematics.

The AP activities are in line with the main European and international activities, as specified by several Call of the H2020 Work Program and in line the preliminary aspects of FP9. In particular the activities are central with the document of G7 2017 "Data Science: a game changer for science and innovation", the G7 2018 on “The digital future”, with the EC statement of 25th April 1018 titled “Artificial Intelligence for Europe. Finally, the AP activities are linked with other CNR DIITET APs, such as the AP Cyber Security, the AP Cultural Heritage, the AP Health and Well-Being, and the AP Applied Mathematics.

The AP activities, together with the involved CNR Institutes and research groups, is an international reference point in the various research and development sectors, as demonstrated by the large number of European, international, national, and regional projects, the important collaboration with industries and universities, the results on patents and dissemination activities.

Finally, the AP research and development activities involves 15 CNR Institutes (CNR-ISTI, CNR-IMATI, CNR-ITC, CNR-IIT, CNR-ISTC, CNR-IREA, CNR-IEIIT, CNR-ICAR, CNR-IASI, CNR-IAC, CNR-ITIA, CNR-IFAC, CNR-IGI, CNR-IRC, CNR-ISTEC), for a total of around 600 person-months per year.
AP4 E-INFRASTRUCTURES

EXECUTIVE SUMMARY

E-Infrastructures (i.e. the comprehensive ICT infrastructures that are needed to enable the complex, multi-disciplinary and globalised practice of modern science), with their resources and services are at the core of current changes towards Open Science and Open Innovation. They represent a global phenomenon in which Europe plays a key role through the funding of pillars such as the European Open Science Cloud (EOSC) and the European Data Infrastructure (EDI).

The “e-Infrastructures Project Area” collects the research contributes of scientists affiliated with Institutes of the CNR Department of Engineering, ICT and Technologies for Energy and Transportation (DIITET) in this context. These contributes spans across e-infrastructures in the area of Network, Computation and Data and along all the dimensions introduced by the recently published EC Staff Working Document on Implementation Roadmap for the European Open Science Cloud (i.e. Architecture, Data, Services, Access & Interfaces, Rules, and Governance).

The largest engagement is on topics related to the shaping and development of powerful and effective e-Infrastructures offering data management services. Part of the activities in this context concern the design of generic enabling facilities for data infrastructures and for the EOSC federation while others are related with domain specific solutions within Research Infrastructures facilitating scientists in operating in their respective fields. All these activities foster Findable, Accessible, Interoperable and Reusable (FAIR) data management.

The above research activities on data related infrastructures are nicely complemented by others on outstanding national project in network infrastructures and on distributed computing for Big Data.

As a whole, the institutes participating in this Project Area (ISTI, IIT, ICAR, IMATI, IREA) exhibit a good expertise that can be mobilized in supporting inter-department, national and European initiatives on e-Infrastructure, Research Infrastructures, Open Science and Open Innovation.

1. STATE OF THE ART OF THE RELEVANT SCIENTIFIC AREA

The dramatic increase in the amount and variety of data being produced and made available opens new scenarios to carry out research, develop and implement public policies, and expand the market with innovative products and solutions. In parallel, the emergence of the Open Science approach is changing the way in which scientific research is carried out, fostering a much more collaborative approach and new ways of diffusing knowledge.

E-Infrastructures\(^1\) are at the core of this change: they offer functionality that support communication and knowledge production workflows, from the basic data storage and curation, to data access, exchange and analytics till data publication. They are set up to provide basic functionality that is common to more or less large, remotely disperse, community of practices. The functionality is offered “as-a-Service”, meaning that is made available by an online service operated by the e-Infrastructure provider. E-Infrastructures are completely transparent to their users. All the technical, organisational and operational tasks needed to deliver the service are hidden and up to the provider. These characteristics make e-Infrastructures enablers for addressing big scientific challenges, reducing costs, complexity and time required to develop and operate the necessary applications.

The role of e-Infrastructures as basic technological instruments able to boost innovation in the research, societal and economic contexts, was officially recognised by the Commission in its April 2016 Communication

on the “European Cloud Initiative”\(^2\), as a part of the Digital Single Market Strategy. This Communication launched the **European Open Science Cloud (EOSC)** as a mean to enable data to be used throughout the value chain for scientific, societal and industrial purposes. A key concept of EOSC is to offer to every European researcher and citizen the possibility to access and reuse all publicly funded research data in Europe, across disciplines and borders. The same Communication laid the foundations for setting up a **European Data Infrastructure (EDI)**. EDI is envisaged to underpin EOSC by providing world-class HPC capability and high-speed connectivity as well as leading-edge services benefitting from them.

In the Commission’s vision EOSC is expected to be built as an open and evolving system-of-systems leveraging existing research supporting infrastructures and other resources, meaning with this generic network, compute and data infrastructures, domain specific research infrastructures (RIs)\(^3\) and thematic platforms, like for example, the Copernicus Data and Information Access Services (DIAS) offering services facilitating users in accessing Earth Observation data and information stemming from the Copernicus programme.

EOSC is also expected to (i) be able to support multidisciplinary and cross-disciplinary research, (ii) facilitate FAIR\(^4,5\) data management and (iii) enable cooperation and as early as possible sharing of research outcomes.

The realization of the EOSC vision is raising many new challenges in the e-Infrastructure related research sector. By exploiting the model proposed in the “EC Staff Working Document on the Implementation Roadmap for the European Open Science Cloud”\(^6\) endorsed by the EU Competitiveness Council of the EU\(^7\) these challenges can be organised according to six actions lines:

1. **Architecture**: the EOSC architecture will be built as a federation of e-infrastructures, RIs and other resources organised around a federating core and providing access to a wide range of publicly funded services supplied at national, regional and institutional levels, and to complementary commercial services. Implementing this vision requires, among the others, the identification of what are the optimal core services, how they can be offered at a sufficient level of quality, how interoperability at all levels can be achieved, and how to minimise the cost of using them by third-parties.

2. **Data**: EOSC will promote FAIRness oriented data management practices and tools. The EOSC settings calls for solutions dealing with the “big” dimension of data, in terms of volume and variety. Realising this vision requires the design and development of services and solutions (e.g. metadata, standards, mediators, preservation approaches) aiming at facilitating the findability, accessibility, interoperability, and reusability of data across the boundaries of the domain and communities they originate from.

3. **Services**: EOSC is expected to be a rich environment offering a wide range of services covering users’ needs. This requires to design and develop services and approaches providing researchers with innovative facilities improving the tasks they are called to perform in all the phases of a scientific life cycle: from the formulation of a research idea to the collection of data, their analytics and the FAIR “publishing” of the results.

4. **Access and interfaces**: EOSC will offer a broad range of mechanisms and interfaces for accessing its facilities including simple ways to deal with open data obligations and to access research data across different disciplines. This demand the design and development of a rich array of entry points for EOSC.

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\(^3\) RIs are domain-specific infrastructures called to provide their communities with facilities, resources and IT related services that are used to conduct top-level research in their respective fields.

\(^4\) **FAIR** is an acronym that stands for “Findable, Accessible, Interoperable and Reusable”.


\(^7\) Draft Council conclusions on the European Open Science Cloud (EOSC) [https://eoscpiilot.eu/sites/default/files/council_conclusions_on_the_european_open_science_cloud_eosc.pdf](https://eoscpiilot.eu/sites/default/files/council_conclusions_on_the_european_open_science_cloud_eosc.pdf)
services access, e.g. an overall web-based portal, APIs to EOSC services, community tailored working environments.

5. **Rules**: Being a multi-stakeholder driven and evolving environment EOSC must be regulated by rules for participation for the different EOSC consumers and providers. These must take into account the diversity of actors in terms of role, location, maturity level, commitment level, and scientific discipline. This line includes models to represent these variety of rules, algorithms and solutions to automatically support the validation ad monitoring of these rules.

6. **Governance**: EOSC needs a suitable governance framework aiming at ensuring EU leadership in data-driven science. This demands for mechanisms envisaging automatic representation, monitoring and reporting of KPIs, costs, activities, etc.

2. CONTRIBUTION TO THE RELEVANT SCIENTIFIC AREA

The contribution of DIITET Institutes to this PA is summarised below according to a matrix of competencies based on the six action lines driving the development of EOSC (cf. Sec. 1) and the three typologies of e-Infrastructures: **Network, Computing, and Data**.

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**IMATI** is primarily working on Data Infrastructures. In particular:

- **Data**: the focus is on (i) definition and reuse of metadata and ontology models in the context of standardization efforts to ease data interoperability and information discovery; (ii) reuse and extension of Linked Data architectural pattern for mapping, connecting and indexing heterogeneous information from different sources; (iii) definition of methods addressing provenance provision for reproducibility and dependability.

- **Services**: the focus is on (i) 3D content-based multi-criteria search methods; (ii) data processing services; (iii) workflow composition and execution, to integrate heterogeneous software tools and to access and exploit a potentially large set of computational resources; (iv) methods to provide value-added information for applications (e.g. Medicine, Environment).

**IMATI** develops and maintains four e-infrastructures providing community tailored services: **VVS** supports research in visual data, i.e. on computational methods for the analysis, processing, visualisation, and reconstruction of 2D/3D digital representations. **DRIHM** and **EXTras** are based on the science gateway paradigm and rely on **PRACE** and **EGI**. **GeCa RDC** supports researchers in finding bibliographic resources.
ISTI is actively involved in the design and development of computing and data infrastructures:

- **Architecture:** It is leading the EOSCpilot project task called to design the architecture of EOSC. In doing that it is envisaging an architecture driven by few key principles, i.e. system-of-systems paradigm, as-a-Service provision, rules of participation regulating policies and procedures, FAIR principles. The proposed architecture model envisages a set of service typologies needed to comply with these key principles and to contribute to the implementation of the EOSC vision. ISTI is also leading the design and development of two pan-European infrastructures D4Science.org and OpenAIRE. D4Science.org is an infrastructure specifically designed to provide research communities with Virtual Research Environments, i.e. web-based working environments customised to serve specific needs (services, data, capacity). OpenAIRE is contributing to the development of a global Scholarly Common supporting researchers, funders and other actors in research institutions to comply and monitor Open Access/Open Data/Open Science mandates in Europe.

- **Data and Services:** It is involved in the designing and development a rich array of services and approaches supporting all the phases of data management and implementing FAIRness and Open Science state of the art practices. Such services are contributing to two large software frameworks (i.e. D-NET and gCube) enacting, respectively, the implementation of D4Science.org and OpenAIRE. Services include (i) a data analytics platform specifically conceived to support researchers in sharing their analytics methods and tasks; (ii) a data integration and linking service supporting the development of a rich scholarly communication graph linking publications, datasets, people, organizations, projects, and funders aggregated from a variety of data sources; (iii) new generation repositories specifically conceived to support Open Science deposition.

- **Access and Interfaces:** It is involved in the definition and development of the concept of “Virtual Research Environment” as an approach to provide researchers with seamless and focused access to the facilities of their interest.

- **Rules and Governance:** It is involved in the EOSCpilot project activities called (i) to envisage the governance model of the forthcoming EOSC and (ii) to identify and develop a set of rules of participation for the various EOSC actors. In this role, it is conducting research on identifying what type of data models, algorithms, protocols and IT services are needed to automatically support the monitoring and assessment of these rules.

IREA mainly focused on tools and practices enabling FAIR data management and on open thematic services:

- **Data and Services:** IREA expertise is enhanced by its involvement in well-recognised ESFRI RIs, i.e. LifeWatch, EPOS and LTER, where all EOSC dimensions and recommendations are applied and tested. LifeWatch has been recognized as LifeWatch-ERIC (2017) and include Italy (Service Center of the e-infrastructure) as major pillar. In this context CNR has built the national Joint Research Unit LifeWatch-ITA. LTER is the global network of Long-Term Ecological Research sites. Its European branch, LTER Europe, is in the ESFRI roadmap to become an ERIC aimed at building its distributed and interoperable data infrastructure. EPOS is developing a pan-European research infrastructure in the field of Solid Earth.

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8 Candela L et al. (2018) Initial EOSC Service Architecture. EOSCpilot Deliverable D5.1 [https://eoscpilot.eu/content/d51-initial-eosc-service-architecture](https://eoscpilot.eu/content/d51-initial-eosc-service-architecture)


Science. EPOS involves 24 countries and is included in the ESFRI roadmap to become an ERIC, hosted in Italy, in 2018. At national level, the community is organized in a JRU, set up in 2017 and coordinated by INGV. The implementation of EPOS is co-financed by the EC (H2020 EPOS-IP). In EPOS-IP, IREA is coordinating the development of the Thematic Core Service Satellite Data.

Within these RIs IREA research focus is on: infrastructures components; thesauri and ontologies; standard catalogue services; interoperable sensor services; data quality methods and services; modelling and GIS services; systematic and on-demand processing services for Earth Observation data.

ICAR performs activities mainly centered on the service action line applied to distributed computing for big data:

- **Services:** ICAR focusses on the development of a system based on a community of cores that is inspired by the collaborative model used in BOINC while implementing an ad hoc rewarding strategy similar to Bitcoin mining. As this solution does not require in principle any specific user skills (participants can join the network by simply providing their underused computational resources) the approach can be seen as a hybrid crowd as tasks can be solved by computer-based resources. ICAR researchers are also quite active in projects for IoT networks building and analysis. They have relevant skills on Data Mining, Machine Learning and Behavioural Analysis of huge amount of data coming from distributed environments.

IIT is primarily active in dealing with network infrastructures service development:

- **Architecture:** IIT is dealing with the design of the VoIP infrastructure of Tuscany Region, which allows Public Administrations to phone each other via Internet using the same numbers of PSTN. Moreover, IIT is cooperating with the DCSRRI-CNR\(^\text{13}\) to plan the evolution of the CNR network. Regarding network infrastructures design, evolution and monitoring, IIT is performing activities related with Rules and Governance domains by participation in: (i) IPv6 Italia, whose mission is to provide technical leadership and innovative thought for the successful diffusion of IPv6 in Italy, and (ii) GARR WGs, where new networking services and technologies are studied and experimented.

- **Data and Services:** regarding network infrastructure services, IIT is involved in (i) developing 6MoNPlus, a SW collecting router-advertisements and discovering IPv6 multicasts, ARP and DHCP broadcasts to neutralize rogue IPv6 routers and DHCP servers and (ii) Botnet discovering where the main goal is to determine how botnets spread out over the Internet and to collect, analyze and classify malware samples. Monitoring activities are based on honeypots.

IIT is also active in network and data infrastructures with studies and innovative technological solutions for the realization of complex Internet services: (i) the .it Registry is an international service with a very complex architecture. Great emphasis is given to the need to have a reliable, trustworthy, resilient and competitive system; (ii) a study on Internet diffusion is carried out, which uses the “domain name” endogenous metric, a unique methodology at a European level, based on the “Penetration Rate”. Diffusion is described at a national, macro-area, regional and provincial levels; (iii) a project is running to monitor the quality of .it DNS in order to create an integrated system able to point out abnormalities concerning the supply or use of the DNS service; (iv) an “in house” crawling system with a semantic engine has been developed to analyse, in real time, the Internet diffusion of the Agrifood, ICT and Tourism sectors in Italy.

The researchers involved in the describe PA also participate actively in several international working groups and initiatives aiming at identifying possible solutions, approaches and standards to be applied in the e-

\(^{13}\)“Direzione Centrale Supporto alla Rete Scientifica e alle Infrastrutture”, the executive office of the National Research Council of Italy responsible for the Institution infrastructure.
Infrastructure development, like *W3C working groups* (e.g. W3C-DWBP - Data on the Web Best Practice\(^\text{14}\), W3C-DXWG - Data Exchange Working Group\(^\text{15}\)), *RDA\(^\text{16}\) working groups*, and *INSPIRE\(^\text{17}\) working groups*.

3. IMPACT

The CNR researchers involved in the e-Infrastructure PA are playing key roles in shaping the development of the forthcoming EOSC as a whole as well as of its constituents (e-Infrastructures and RIs).

By leading the EOSC system architecture design in the EOSCpilot, ISTI is largely contributing to clarify and framing how it will be structured. On a more focused area IMATI, by participating in the EGI User Community Board, is contributing to delineate the EGI’s production infrastructure, to define usage policies and to prioritise requirements and issues.

By improving and enriching the capabilities of e-Infrastructures and thematic Research Infrastructures the activities of the Project Area have also a large impact on different sectors of our society. The OpenAIRE infrastructure, for example, is now (June 2018) providing access to 24+ Million of publications, almost 600K datasets from 11,785 repositories and Open Access journal and it is supporting the European Commission and other funders in monitoring the Open Access mandate. The D4Science Infrastructure already showcases the potentiality of the forthcoming EOSC by supporting scientific and societal challenges in contexts like agroclimatic and economic modelling, food safety risk assessment, food security (*AGINFRAplus*), sustainable growth in the marine and maritime sectors, marine spatial planning, aquaculture economy (*BlueBRIDGE*), environmental data management (*ENVRplus, RI cluster*), history, language studies, cultural heritage, archaeology, and related fields across the (digital) humanities (*PARTHENOS, RI cluster*), and smart cities, human mobility, poverty indicators, spatial analysis macroscopic human flows, etc. (*SoBigData*). In June D4Science operate 129 Virtual Research Environments (VREs), serving 5000+ users from 44 countries with a 99.8 service availability. A number of agreements with international organisations, like FAO, are being signed to use what has been developed in the context of international fisheries and marine biodiversity monitoring activities.

Other societal sectors are addressed by IREA by contributing to development of LifeWatch and LTER RI through projects such as *RITMARE* (the Italian flagship Project in marine research), *NextData* (Italian Project of interest), *eLTER* (H2020 Long-Term Ecosystem Research in Europe), and *ODIP* (H2020 Ocean Data Interoperability Platform). Moreover, IREA’s activities in EPOS RI have important effects on the EOSC galaxy (namely, H2020 EOSC-hub and OpenAIRE-advance projects), and the ESA’s Geohazards Exploitation Platform project and DIAS initiative.

Some of the services and activities falling under the PA umbrella have also an important impact at National level. For instance, IREA plays the role of Center of Competence of the Italian Civil Protection Department and has established an agreement with *MISE* to monitor surface deformations affecting the Italian territory with particular emphasis on sites interested by activities to store or extract hydrocarbons. IIT is assisting the national level of Italian public administrations in managing and updating the networking infrastructure and the diffusion of the IPv6 protocol. Moreover, IIT is operating the .it Registry that (a) currently counts more than 3.1 million domain names and, in terms of number of domain names, it is the 6th Registry at European level.

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\(^{16}\) Research Data Alliance (RDA)  [www.rd-alliance.org](http://www.rd-alliance.org)

level; and (b) has more than 1,250 contracts with ISPs, Telco operators and public and private bodies. Finally, IIT has established a collaboration with the Italian Defense General Staff (Stato Maggiore delle Difesa).

The research activities described so far naturally map and interrelate with others related to the development of thematic Research Infrastructures performed in different CNR Departments, like the “Earth system science and environmental technologies”, the “Social sciences and humanities, cultural heritage (DTU) and the “Biomedical Science” ones.

Through the above described activities CNR can also actively contribute to the planned ICDI (Italian Computing and Data Infrastructure). This is a forum of major Italian Research Infrastructures and e-Infrastructures representatives, with the aim of promoting synergies at the national level and of harmonizing the Italian contribution to European and global challenges in various initiatives, including EOSC, EDI and HPC. In the long term, the vision aims of the forum is to create a national coordination body that could represent Italian infrastructures, being capable to interact with national and European initiatives and effective in facilitating the Italian participation in their design, governance and operation.

4. EMERGING RESEARCH CHALLENGES

The effective and massive use of e-Infrastructures and RIs across sectors opens completely new application scenarios but also underpin an ample variety of research challenges. The Architecture of the overall landscape is still unclear. e-Infrastructures and RIs are evolving, new ones are emerging. How can all the provided services be used seamlessly, how they can be used across infrastructures boundaries in complex workflows and how these workflows can be executed by respecting their terms of use, trust, security and service time requirements are relevant open questions. Regarding data the challenges are even more complex. How infrastructures should ensure an effective and mostly automatic implementation of FAIR principles and, especially, how to fully support data products traceability and reproducibility are among the many open questions. The availability of data stored in repositories or automatically collected by observing infrastructure users’ behavior opens to an unlimited number of new services for knowledge extraction. Infrastructures are expected to offer transparently the capabilities for such, often complex extraction, based on a plethora of new paradigms and approaches.

5. CONCLUSIONS (2000/2200)

The CNR Institutes participating in the e-Infrastructures PA (i.e. ISTI, IIT, ICAR, IMATI, IREA) address complementary aspects of the Infrastructures research and development. The major involvement is on research related to data infrastructures, be them generic ones or embedded in thematic research infrastructures. Other activities pertain national projects in network infrastructures and on distributed computing for Big Data. The research groups involved witness the lively activity of the PA, with:

- the participation/coordination of twenty-five ongoing projects at international and national level;
- more than twenty hw/sw facilities, including clusters, servers, portals, platforms, FAIR enabling services, networking enabling architectures and applications, made available inside and outside CNR;
- an effort of eighty-three people;
- unique national facilities such as the .it Registry and the P-SBAS DInSAR Processing Chain (for Civil Protection).

These on-going research activities place DIITET in a relevant position for designing and building Networking, Computation and Data infrastructure services tailored for public and private bodies, as well as to serve in consultancy, evaluation and promotion of initiatives in the field. Through these activities the PA can also to contribute to the Open Science challenge, to EOSC and to any national initiative in this area that may emerge in the future (e.g. ICDI). By increasing the quality, capacity and functionality of the infrastructures these activities also facilitate a more extensive and systematic exploitation of infrastructures in addressing a variety of societal challenges (e.g. civil protection, monitoring of environmental and economic indicators, food
production assessment and monitoring) and in supporting Open Innovation (i.e. the early exploitation of research results in the Industrial sector).

The potential of the described activities is largely amplified by the multidisciplinary nature of CNR. There are many other activities in other PAs of the same and of other CNR Departments that can benefit and can complement what has been presented. A strict synergy and cross-fertilization among all these activities would indeed allow CNR to increase its key role in many National and International contexts.
**AP5 CYBER SECURITY**

**EXECUTIVE SUMMARY**

Cyber security is a main research challenge because 1) citizens’ everyday life relies on cyber systems, e.g. energy distribution, and healthcare, and their failures can affect millions of people 2) faults can be caused by people thousands of kilometers far from the affected area 3) one of the main sources of data helping cyber attackers is the people’s unaware digital behavior. Thus, a huge effort is needed to prevent, detect and react to cyber-attacks. Moreover, each cyber system often has specific needs, e.g. confidentiality is needed in banking systems, whereas industrial systems put first availability.

The CNR Project Area **Cyber Security** fully covers all the above issues by addressing the following topics:

1. **Cyber-Physical Systems (CPS)** join security and safety needs, i.e. cyber-attacks may lead to injuries to human beings and loss of lives.
2. **Network security** will investigate several issues as Slow Denial-of-Service (DoS) attacks as well as monitoring TOR (The Onion Router) WEB network for illegal activities.
3. **Intrusion Detection and Protection** by means of energy-based security, i.e. the measure of (abnormal) power consumption.
4. **Privacy** risk assessment and privacy-by-design methods are needed to guarantee high protection of personal data to enable (big) data analytics.
5. **Information Sharing and Analytics** (ISHA): the design of machine learning, artificial intelligence and data analytics techniques able to make sense of large amounts of data.
6. **Cyber-intelligence on Social Media**: techniques for gathering and analyzing data from Social Media for Intelligence purposes.
7. **Secure Software Engineering** assures integrated approaches to face continuous evolution and criticalities rising during all the development cycle of software-intensive systems.
8. **Access Control and Trust Management** are among the most important security tools in large distributed systems.
9. **Cryptography** is a keyword: reliable, efficient implementations of state-of-the-art algorithms and protocols are required, and must be assessed w.r.t. high-performance code breaking platforms.
10. **Cloud Security** concerns the protection of data and resources that are stored and shared on the Cloud, and of the business or research process that are outsourced to the Cloud.
11. **Cyber insurance** is a new domain: damages caused by targeted attacks need new mathematical models and regulations w.r.t. accidental events.

The following sections have a sub-section for each of the above topics, in the same order.

**1. STATE OF THE ART OF THE RELEVANT SCIENTIFIC AREA**

1.1 CPS

W.r.t. the ICT world, Cyber Physical Systems (CPS) have critical security needs due to hw/sw limitations of devices, constraints on power consumption, real-time scheduling and communications, and strongly interconnected security and safety [TII13]. The evolution of CPS towards Industry 4.0 and Factory of the Future exacerbates these needs.

1.2 Network Security

- Slow DoS attacks. Concerning the design of innovative cyber-attacks, relevant contribution to the research world was provided, by introducing the term “slow dos attack”, relatively to last generation denial of service attacks, also proving for the first time that such threats can be successfully executed on not performant hosts [IGP16]. Also, innovative protection methodologies, applied to different last generation cyber-threats, were proposed.
- TOR WEB. The exploration and analysis has flourished in the recent past on Web graphs, but not on the TOR network. Little information is available about the topology of the TOR WEB graph and its relation with content semantics [TOR17].

1.3 Intrusion detection and protection

The detection of malware using information hiding, e.g. covert channels, is very hard: the resulting throughput of data for such malicious communication is usually very limited and each covert channel highly depends on how the information is hidden and which hidden data carrier is used. A recent approach relies on high-level indicators to decouple the detection from the underlying technology. In this vein, energy-based security allows to exploit abnormal consumptions to detect information-hiding-capable threats [LC1].

1.4 Privacy

Many practical and impactful services based on big data analytics can be designed in such a way that the quality of results can coexist with high protection of personal data by providing methodologies for privacy risk assessment [PPP+18] and applying a suitable privacy-by-design methodology.

1.5 Information Sharing and Analytics

Information Sharing and Analytics (ISHA) concerns the design of machine learning, artificial intelligence and data analytics techniques able to make sense of large amounts of data. These techniques are particularly effective in identifying system/user anomalies [A+17], and in predicting/preventing security threats and adversarial attacks.

1.6 Social Media

Social media data gathering and analysis for Intelligence purposes, mainly in the fields of hate speech detection, user interaction analysis and face similarity identification; malicious accounts are responsible for manipulating the public opinion [CDP+15] thus requiring techniques for modeling and detecting them by analysing user profiles, posts, and social links.

1.7 Secure Software Engineering

The integration of the proper security management and control during all phases of the development life cycle of software and systems is able to avoid critical security flaws and vulnerabilities. In particular security-by-design is now considered as key solution in different application domain [BCD+17].

1.8 Access Control and Trust Management

Access control and trust management are relevant security mechanisms in large and open distributed systems as internet. This also entails the capability to determine trust levels complex architectures [DMM+18].

1.9 Cryptography

Modern cryptography is a tremendous tool for cybersecurity, and its importance is supposed to increase in the next decades. Three characteristics in the current development and deployment of information services are indeed the multi-tenancy of computer environments (as in DaaS, [GS1]), the multi-authorship of data (as in blockchain systems), and the multi-security for user end points. These three factors are jointly weakening traditional cryptographic approaches, since they break traditional chains of trust, and expose both data and applications to threat conditions which heavily depend on context and can frequently change over time. New cryptographic approaches are required because of emerging cipher-breaking platforms, too. Cost-affordable massive farms and large-scale networks of high performance computing units (eg; GPUs, ASICs) are already used for this purpose [CUB17], and quantum computers are on the way.

1.10 Cloud Security

The ever increasing adoption of the Cloud for executing applications and sharing resources or data, on the one hand gives several performance and cost advantages but, on the other hand, introduces new relevant security issues, being user authentication, even across domains, and authorization for long lasting accesses among the most relevant ones [FGCS16].
1.11 Cyber Insurance

Insurance was only recently applied to the cyber world. The immature cyber insurance market faces a number of unique challenges on the way of its development [AO17].

1.11 Bibliography


2. CONTRIBUTION TO THE RELEVANT SCIENTIFIC AREA

2.1 CPS

Challenges in securing CPS are dealt with the following research activities 1) description of the CPS by means of a formal model able to cope with all the characteristics of its components, their interactions and the required security policies 2) development of a sw tool able to check whether or not the above model satisfies the security policies 3) study and test how modern communication and service provisioning paradigms (such
as SDN and NFV) can improve the security of CPS 4) performance analysis and test of industrial stateful network firewalls in order to guarantee they can match the high performance required by CPS with real-time constraints, where special purpose communication protocols are used.

2.2 Network Security

2.2.1 Slow DoS attacks

In-depth studies on attack technologies, carried out with the aim of designing innovative defense systems, provided the ability to contribute to relevant research projects. The focus is not only on critical ICT systems in general, but also on specific infrastructures. Also, penetration testing and security tools investigation is accomplished.

2.2.2 TOR WEB

Research activity done in the EU-ISEC IANCIS project has contributed to improve knowledge about TOR Dark Web, providing: a survey over the possible TOR WEB exploration approaches and their limitations; the selection and adoption of a relevant set of metrics for evaluating actual TOR hidden services data; a novel in-depth investigation over the TOR WEB topology; an in-depth analysis of the relationship between the topics found in English TOR pages and the TOR WEB topology.

2.3 Intrusion detection and protection

Challenges in information hiding and network steganography require the investigation of novel detection techniques. Possible new ideas to investigate are: i) statistical / machine-learning techniques able to parse software artifacts (e.g., the distribution of bytecode of executables or the composition or statistics of traffic patterns) to detect the presence of information-hiding-capable threats, and ii) define energy or computational metrics aimed to capture the presence of threats covertly exchange data in emerging scenarios including IoT nodes, high performance computing / parallel systems or network and home appliances. In both cases, scalability issues will be investigated as to allow their implementation to monitor production quality settings or to protect large-scale deployments or wide networks.

Besides, another important challenge deals with energy-aware / green security, which aims at understanding the impact of security on the energy footprint, both for optimization and detection purposes.

2.4 Privacy

Challenges arising from the implications of privacy and data protection issues in ICT world are dealt with the following research activities: 1) designing of data transformations following the privacy-by-design principle for making data private while preserving data quality; 2) designing data mining and big data analytics approaches which by-design guarantee privacy protection; 3) designing privacy-by-design technologies that guarantee corporate privacy protection while outsourcing data mining tasks, i.e. the third party cannot infer sensitive information both from data and from extracted knowledge; 4) development of technologies for privacy protection: from data usage control to privacy-aware secure multi-party computation; 5) studying methodologies and tools for software engineering specific for privacy protection; 6) studying methodologies for assessing the privacy risk level by considering different and realistic attack models that are particularly suitable for specific type of data.

2.5 Information Sharing and Analytics

Challenges in ISHA requires the development of techniques for 1) security analytics, based on behavioral profiling, to detect malicious activities and devise models of trust; 2) social sensing for prediction of sensitive information diffusion flows and secure information sharing; 3) attack prevention/response based on machine learning and AI to improve reaction to incidents; 4) privacy-preserving information handling based on theoretically guaranteed models of privacy.

2.6 Social Media

Techniques for gathering relevant amount of data from Social Media; big data analysis for Intelligence purposes in the following fields:
• Malicious accounts detection on Social Media, analysing user behaviour, relations and posted content
• hate speech detection, performing NLP analysis on user posts and comments
• analysis of different types of interactions between users, analysing the evolution of their behaviour considering space and time
• analysing multimedial content, in order to perform face similarity detection on posted images

2.7 Secure Software Engineering
Secure Software Engineering involves different activities in all the phases of development life cycle. They include: 1) secure requirements and quality attributes collection, analysis and design 2) software or system construction, verification, validation and evaluation 3) on-line monitoring, control and assessment of specific security properties and metrics 4) Integration tools and methods for automate security management into all the software process.

2.8 Access Control and Trust Management
Challenges of security mechanisms in large distributed systems promote the research activity in different areas: 1) Verification and Validation (V&V) of access and usage control systems to protect (personal) data and resources against unauthorized, malicious or erroneous usage; 2)Technology transfer of standard V&V approaches in the context of security and privacy; 3) Effective strategies for test case prioritization and selection 4) Test suite effectiveness assessment through mutation analysis; 5) Compliance assurance of the rules on international transfers of personal data; 6) Development of model-driven approaches for dynamic access and usage policies specification and evaluation.

2.9 Cryptography
Current main activities in cryptography are as follows. New full-text indices in minute space for performing fast pattern-search queries and evaluation on nucleotide sequence collections in DaaS (Database-as-a-Service) models. The E2FM-index can save about 95% of storage and search for patterns in times of milliseconds. Network architectures and protocols for the management of multi-authorship, distributed databases: functionalities and issues of the promising blockchain technology are under investigation, and a near join work with the DI - University of Milan will explore fairer computing approaches than PoW (Proof-of-Work) and PoS (Proof-of-Stake) systems. On the cipher-breaking side, a smart effective general framework implementing a parallel GPU-based version of the CUBE attack has been designed and implemented. The obtained results allowed to improve the state of the art, managing to attack stream ciphers like Trivium. Other brute force and dictionary-based attacks have been successfully devised and implemented on GPUs, allowing among other things to break the BitLocker encryption system.

2.10 Cloud Security
The research challenges on Cloud security concerns several areas such as: Identity Management and Authentication mechanisms, with particular reference to Federations of Clouds, enhanced mechanisms for Access Control (such as the Usage Control ones) for services, resources and data that shared on the Cloud, virtualization security in multi-tenant environments, data privacy, aspects of compliance, security services (e.g., Policy as a Service), and Cloud governance security. The research activity also takes into account the security issues coming from the integration of Cloud with the Internet of Things and the evolution to Edge computing. The study of the security risks related to the adoption of the Cloud in Public Administration, for example for the management of the citizen’s Electronic Health Record is another relevant research topic.

2.11 Cyber Insurance
Cyber security insurance is designed to mitigate losses from a variety of cyber incidents, including data breaches, data theft, business interruption and network damage. Despite a slow start and many problematic issues, the cyber insurance market grows and Insurance companies are increasingly offering such policies, in particular in the USA, but also in Europe. A robust cyber-security insurance market could help to reduce the number of successful cyber-attacks by promoting the adoption of preventive measures in return for more
coverage and encouraging the implementation of best practices by basing premiums on an insured level of self-protection.

Considering this topic from a business or an economic perspective too, is strongly required. In light of these considerations, the main contributions in this area concern: studying market solutions for cyber insurance, improving knowledge on peculiarities of cyber insurance, pricing and risk measures estimation, effect of security interdependence, analysis of cyber insurance as an incentive to invest in security.

3. IMPACT

3.1 CPS

CPS are connected to both the physical world, and ICT systems. Thus, addressing their security needs by a multi-directional approach able to cope with all the system components, their relationship and the whole cycle-life, from the design to decommissioning, through all upgrades and updates can improve the way such systems are perceived, also by citizens and users, and contributes to a more secure evolution of these systems, also in an inter-system perspective.

3.2 Network Security

3.2.1 Slow DOS attacks

Concerning cyber-security, the aim is to improve security capabilities for devices, networks and infrastructures to prevent the world from being involved in possible cyber-attacks on individuals or communities.

3.2.2 TOR WEB

A further in-depth analysis of the obtained experimental data helps discovering and describing novel relationships between topology and semantics, and allows a careful reasoning of these results. Indeed, our work shows interesting characteristics of the TOR WEB graph that relate topic semantics and WEB graph topology. Such findings contribute to a better understanding of the TOR usage and of contained information, allowing for more effective Police investigations.

3.3 Intrusion detection and protection

Currently, it is important to investigate new, sophisticated ways of hiding data in communication networks as this allows to detect vulnerabilities in the existing network protocols, which can lead to their malicious exploitation, e.g., by enabling “invisible” confidential data leakage or empower a new-wave of advanced persistent threats. Therefore, this may improve the security of existing protocols and propose some countermeasures to mitigate threats, which can also target transitional scenario such as IPv4/IPv6 ones.

3.4 Privacy

Large datasets recording human activities are key enablers of a new wave of knowledge-based services, as well as of new scientific discoveries. Unfortunately, the use of human data may raise the concern on leakage of personal information. Therefore, organizations need to exploit the advantage analyzing available big data while preventing privacy violations, which may result in negative economic and social impacts. Addressing privacy issues by developing technologies and methodologies for assessing and guaranteeing privacy protection by-design may help in setting the data free.

3.5 Information Sharing and Analytics

ISHA for cybersecurity can significantly reduce the risks and effects of attacks, by revolutionizing the way incident response to cyber events is handled. Coupling machine learning and AI techniques with a mathematically guaranteed notion of privacy to augment cybersecurity allows to automatically handle and make sense of complex data flows, detect/prevent attacks, reduce the risks and the effects, and react to breaches while preserving the privacy of data contributors.
3.6 Social Media
Tools have been developed and released to Italian LEAs in order to gather data from Social Media and using BigData techniques in order to:

- classify users as malicious/legitimate
- analyze user interactions
- perform face similarity on collected images
- perform hate speech detection on collected messages
- provide tools for performing complex visualizations

3.7 Secure Software Engineering
Secure software engineering is recognized as an effective and efficient means for: increasing the overall quality level of the developed software or systems; decrease the risk of vulnerabilities and security flaws; drastically reduce the cost and effort for the management and correction of security problems; increase the user security perception and confidence in the final products.

3.8 Access Control and Trust Management
Large scale distributed systems and smart environments are requiring complex access control as well as trust management. On the one hand, guaranteeing access to resources is one of the paramount aspects of security. In open frameworks, where the environment is not closed, the necessity to monitor the behaviors of entities or of applications is crucial.

3.9 Cryptography
According to the next set of laws by which the EU Commission intend to strengthen and unify data protection for all individuals in the new global digital market, cryptographic algorithms and software will play a major role in the near future. The goals of the action line Cryptography are the design of new cryptographic algorithms and protocols, and the integration of existing state-of-the-art cryptographic tools for the protection of data and processes in emerging digital services and applications. On the cipher-breaking side, obtained results shed a new light on the effectiveness of massively parallel algebraic-based attacks. Further, other successful brute force, dictionary-based attacks we implemented on GPUs can help to show weaknesses in existing, real-word crypto systems.

3.10 Cloud Security
Security is a key aspect of Cloud affecting its adoption by citizens, companies, and also public entities, in particular for what concerns the execution of critical parts of the business/research processes and the storage and sharing of personal, valuable, and critical data. Hence, the design of proper security techniques that enhances Cloud security, for instance by regulating the access and the usage to the resources shared on the Cloud, would have a great impact on the Cloud adoption.

3.11 Cyber Insurance
Cyber insurance by itself provides a unique opportunity to cover risks, as well to contribute to social welfare. Different technological systems impose different challenges on cyber insurance and, at the same time, provide different opportunities. Moreover, a knowledge of cyber insurance is critical because companies need to review cyber security and resilience considering the role of cyber insurance as part of risk management. From insurers perspective, our research can help defining standardized procedures.

4. EMERGING RESEARCH CHALLENGES
Design and analysis methods for CPS security and safety, also matching performance and timing.
Scalable and energy optimized malware detection techniques.
AI and machine learning techniques to analyze large amounts data and preserve users’ privacy.
Generation of methods to keep the pace with Social Media evolution for Intelligence purposes.

*Health metrics* for health ranking of online social ecosystems.

Definition of new approaches and standards for safety and security integration.
Advanced techniques for distributed trust, including Distributed ledgers.
Design and implementation of new cryptographic primitives and protocols, and their security assessment through cipher-breaking methods exploiting new hardware features.
Research to secure the resources and the data shared and processed on the Cloud in the light of the evolution of Cloud to Edge computing.
Methods to overcome interdependent security and information asymmetry issues in Cyber Insurance.
Analysis methods to cope with increasing size of TOR and its evolving graph and content.

5. **CONCLUSIONS**

The current research activities and proposed approaches are showing good results from the theoretical and practical point of view, with successful publications and collaborations with national and international industrial partners, and public bodies. On the one side this shows that the right way has been taken, but also that more resources and effort are needed to provide adequate solutions in a world where cybersecurity is perceived as a major challenge by both citizens and institutions, and rightly so.

In particular, the use of artificial intelligence and machine learning deserves further investigations: the large and varied amounts of data organization deal with require the design of techniques able to both automatically and precisely detect/prevent anomalous behaviors. In this respect, the AP can play a prominent role and provide both practical and theoretical results.

Research on Social Media Intelligence is producing a strong impact on both scientific research and towards safeguarding from manipulation the information exchanged in our online communities. Emerging challenges need to be faced promptly and strongly, in order to keep pace with the rapidly evolving threats in social media.

Moreover, the different proposed testing solutions adopted in various real world environment have been proven to be effective in detecting security flaws of adopted security systems and improve their overall quality and confidence. Research activity reveals also the necessity of the integration of different knowledge area so to cover the multidisciplinary aspects of large scale and smart environments.

Cryptography is playing a major role because of data and process sharing in modern computing environments. Because of emerging cipher-breaking platforms, it is expected that in the next decade cryptography will be a very active research field.

On the Cyber Insurance side, although it is a desirable option for agents, it has many open issues yet to be resolved by scientists and practitioners.

Novel approaches and treatments are required to ensure the positive effect of cyber insurance on society as well as new standards and practices required for the maturation of the market.

In general, a more and more interconnected world produces and moves huge amounts of data that, on the one side, need to be exchanged, managed, and stored in a secure way, but, on the other hand, these data represent a wider and wider attack surface. For this reason, the future keywords constraints in security will be efficiency, scalability and performance, as, for instance, malware detection techniques require. Missing any of them, will lead to lose the cyber war.
EXECUTIVE SUMMARY

Robotics and control systems are becoming increasingly pervasive and interconnected in our society, and play an essential role for the efficient operation and management of various systems and processes in different applications domains, such as manufacturing, healthcare, agriculture, civil, commercial and consumer, transport and logistics.

In line with the Multi-Annual Roadmap (MAR) for Robotics in Europe, recent and current research in robotics at CNR is aimed to increase the level of abilities of robotic platforms. The objective is to develop new robotic systems with decisional autonomy, able to operate in complex and highly uncertain environments, also cooperating with other robots and humans. Research activities are related to each of the key Technology Clusters defined by the MAR: system development (open source, standards, better systems and tools), safe human-robot interaction (better interaction), mechatronics (better machines), control strategies, perception, navigation and cognition (better action and awareness). Major challenges include AI and innovative hardware solutions for wearable robotics and human-robot interaction, exoskeletons and bio-inspired cognitive architectures, open-ended learning, soft-robotics solutions, design and development of advanced perception systems, multi-robot systems, IoT-Robotics and communication networks.

Research in control systems at CNR is aimed to study complex systems, possibly interconnected, nonlinear, and dependent on a large number of parameters, whose efficient management requires the design of control algorithms developed starting from data measured on the field. The main objective is the design of controllers that are able to guarantee the achievement of given tasks in an efficient and effective way. More specifically, research efforts in this field are mainly devoted to the development of new approaches and algorithms to devise novel control systems that are characterized by fundamental properties, such as stability, accuracy, scalability, optimality, robustness, and reduced computational effort. The various activities can be catalogued in the following main fields: control, estimation and optimization, modeling and identification, probabilistic methods and uncertain systems, networks, and plasma structures. Examples of application are logistic and energy systems, vehicular traffic, biochemistry, medicine, multi-agent systems, robotic networks, datacenter optimization, predictive failure diagnostics, signal and image processing, cyber-physical systems. Major challenges include the development of algorithms well suited to be applied for large-scale, distributed, and decentralized systems, together with the study of novel applications fields aimed at increasing the well-being of humans, such as biomedicine, biology, and reduction of pollutant emissions.

1. STATE OF THE ART OF THE RELEVANT SCIENTIFIC AREA

1.1 Robotics

Robotics technology is becoming ubiquitous in a wide range of different market domains including manufacturing, healthcare, agriculture, civil, commercial and consumer, transport and logistics. Independently of any application domain or technology cluster, it is important to characterize the overall robot system performance in terms of abilities. Abilities allow the state of the art of robot systems to be identified and future targets for improvement of functional performance to be set.

With reference to the Horizon 2020 Multi-Annual Roadmap for Robotics (MAR)\(^\text{18}\) in Europe, the main system abilities can be defined as illustrated in Figure 1. Each ability captures one specific trait of the operation and behavior of a robotic system. Recent and current research activities are aimed at increasing the level of

abilities in order to develop new robotic systems able to operate in complex and uncertain environments, also cooperating with humans.

One of the fundamental robot abilities is the *perception ability*. The use of a robot in a real setting (advanced manufacturing, surgical room, outdoor or indoor applications in agri etc.) implies the control of the operation field and of the surrounding environment. This goal can be reached, for example, through visual servoing, where machine vision or image processing are part of the control system. More generally, perception can be defined as the robot capability to detect objects, spaces, locations or items of interest. It also includes the ability to estimate the robot ego-motion. At its highest level, perception denotes the capability to interpret information and to make informed and accurate deductions about the environment based on sensory data.

![Figure 1 Robot system abilities as defined by the Horizon 2020 Multi-Annual Roadmap for Robotics (MAR) in Europe.](image)

Future robotic systems will have to acquire and process data arising from different on-board devices, as well as from sensors embedded in smart environments or worn by people. Accurate and robust perception is fundamental for a robot to achieve awareness of its surroundings and successfully perform its tasks with limited human supervision, while preserving safety. Although much effort is still being devoted to develop sensors that get individually more and more reliable, to achieve a higher level of safety and integrity, robots should be equipped with multiple sensors featuring different physical properties. Using multiple sensor modalities, the limitations of each sensor may be compensated. Alternative sensing modalities, i.e., using physical principles that are distinct from those used by traditional robotic sensors like vision and LiDAR, have also recently opened many new possibilities. Alternative sensors include radars, sonars, acoustic sensors, odor sensors, depth-sensors, force and contact sensors, thermal cameras or hyperspectral cameras, and their intelligent combination and fusion. The ambition is to develop adaptive perception systems that allow robotic platforms to safely operate also under compromised/difficult conditions or in the presence of humans or animals. Applications of alternative sensing modalities include terrain characterization and geological analysis using hyperspectral cameras, obstacle detection through smoke or heavy dust using radar, or deep-sea exploration and mapping with sonars.19

The interaction between humans and robots, i.e., the *interaction ability*, constitutes an important aspect in current robotic applications. In the future, various artificial embodied agents will populate human living and working environments. The graceful integration of these “quite different” intelligent agents generates a spectrum of different problems. For example we may consider two different scenarios: the collaboration in the factory, and the companionship at home as two extremes of a continuum of challenges for robotics.

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Empowering humans is highly demanded in different areas of robotic. Industries are one of the key user for the development of such technology, since nowadays many onerous tasks (e.g., lifting/installation of heavy components) are still manually made, implying non-ergonomic postures and musculoskeletal disorders.

On one hand, compliant actuation plays a key role in empowering robots design. SEAs use a passive mechanical spring in series with a motor. PEAs differ from SEAs actuators by using a passive mechanical spring in parallel with a motor. Variable stiffness actuators are specifically designed for human-robot interaction tasks, consisting of two motors and spring arrangement, allowing to control both displacement and joint stiffness. On the other hand, control algorithms are also enhancing high-performance human-robot cooperation. Learning-from-demonstration algorithms are exploiting such approaches to directly teach a task to a robot. In order to improve the physical guidance of the manipulator, impedance-based algorithms have been investigated, involving the human dynamics estimation/measurement in the control loop. CNR is facing such research field by both design and control exoskeletons and cooperative arms\textsuperscript{20} in order to enhance human-robot cooperation in industrial onerous tasks.

Scientific research in this context aims to assure complex and natural human-robot interactions for collaborative tasks and social supports. The robot has to fully understand the human behavior in unstructured contexts, including intentions, emotions, and desiderata (cognitive ability). The perceptual data related to humans have to be processed to make a shareable knowledge suitable to exchange information between the robot and the human by natural channels of communication (both verbal and not verbal). The robots acting and interacting in human contexts will have a new specific social role that will take into account different aspects such as wellbeing, safety, health, and productivity, related to human companions and collaborators. An open issue is to explore long terms interactions, making the presence of the robot acceptable and useful for human purposes in real scenarios (i.e., workplaces, houses, hospitals, schools, shops, museums).

Perception and cognition greatly impact on another robot ability, i.e., its decisional autonomy. Decisional autonomy can be defined as the ability of the robot to act autonomously. In this respect, open-ended learning robot research has a key role for the development of architectures and algorithms that allow robots to acquire increasingly complex repertoires of sensorimotor skills by interacting with the environment autonomously or with a mild human supervision\textsuperscript{21,22}. This approach allows robots to self-generate tasks and goals, e.g., based on intrinsic motivations, which in turn allow them to acquire the motor skills based on reinforcement learning algorithms and imitation learning\textsuperscript{23}. Intelligent robots require model-based autonomy solutions\textsuperscript{24} as one of the key features for endowing robotic architectures with suitable decisional autonomy. This is specifically crucial when dealing with robots operating in highly dynamic and human-presence scenarios. A wide Artificial Intelligence research area is focusing on automated reasoning techniques for robotics\textsuperscript{25}. This constitutes an enabling technology for deploying robots capable of adapting to different and evolving scenarios, in particular, when acting with human presence.

Reconfigurability and adaptability in Human Robot Cooperation result in changing layouts, multiple task variants, combinatorial situations of sharing the same spaces between humans and robots, all of which has a substantial effect on safety. Humans are little repeatable and have unknown long-terms effects when exposed to close-quarter robot collaboration. A trend is to develop semi-automated tools able to model and analyze hazardous situations, simulate and anticipate risks (including AI techniques) and propose risk reduction.

While much effort has been devoted to enhance the abilities of single robot systems, many research issues are still open for the development and deployment of multi-robot systems (MRS). MRS can improve the effectiveness of a robotic system both in terms of performance in accomplishing a given task, and of robustness and reliability of the system, which can be increased by modularization. MRS also guarantee higher system configurability and adaptability. Current multi-robot systems research focuses on the coordination of actions and task execution by groups of robots, which can possibly be relatively large (e.g., swarms). The main challenge here is the design of robust and scalable decentralized systems with predictable dynamics, which include both spatial and temporal constraints. For teams of robots communication is a fundamental constraint. In particular, autonomous/cooperative robotic vehicles need improved fast and safety-critical compliant communication networks and protocols, both on the intra- and inter-machine levels, for effective and safe task execution. The presence of human bystanders/cooperators also requires new conceptual frameworks and practical standardized procedures for a high-level safety validation.

New research trends such as soft robotics aim at improving performance in terms of reactivity, adaptability, flexibility, robustness and efficiency, based on solutions coming from nature. In this context, the development of control systems that allow bio-robotic systems to perform tasks in unstructured environments, such as underwater and in dangerous situations, is growing up rapidly.

To expand the applicability of industrial robots, researchers and smart robot integrators not only have to step ahead in the development of further and more advanced motion control, planning, human robot interfaces, sensing, but they also have to trouble to win against the limited interconnectivity of the industrial robots. The ROS-Industrial open source project has been intended to reduce the gap that existed between researchers and manufacturers, in order to start developing state-of-the-art applications for the industry, and to start easing the research activities.

1.2 Control systems

Nowadays, control systems are present everywhere in the world around us, and play an essential role for the efficient operation and management of various systems and processes. As a consequence, the design and engineering of control systems have assumed a crucial importance in the last decades, and they are expected to increase in the next years together with the technological progress of our society. Control systems are ubiquitous. For instance, aircraft and spacecraft, process plants and factories, homes and buildings, automobiles and trains, cellular telephones and networks, together with other complex systems are the proof of the pervasiveness of control technology. The world where we live would simply not be possible without control. The research in control systems aims to study complex systems, possibly interconnected and in most cases nonlinear and dependent on a large number of parameters, whose efficient management requires the design of control algorithms developed starting from the data measured on the field. The main goal is the design of controllers that are able to guarantee the achievement of given tasks in an efficient and effective way. More specifically, the efforts of researchers in this field are mainly devoted to the development of new approaches and algorithms to devise novel control systems that are characterized by fundamental properties, such as stability, accuracy, scalability, optimality, robustness, and reduced computational effort.

As previously pointed out, the application areas of control systems are diverse and multidisciplinary, and include classical engineering sectors, such as aerospace, chemical, electrical and mechanical, and new research fields such as economics, biological systems, social sciences. Examples include logistic systems, vehicular traffic, energy systems, biochemistry, medicine, multi-agent systems, task management and motion control in robotic networks, datacenter optimization, predictive failure diagnostics, signal and image processing, and cyber-physical systems.

2. CONTRIBUTION TO THE RELEVANT SCIENTIFIC AREA

2.1 Robotics

Research activities at CNR in the robotics field are in line with the MAR for Robotics in Europe (constantly updated thanks to the support of the euRobotics AISBL groups that also see the participation and sometimes the leadership of some CNR institutes) and are related to each of the key Technology Clusters defined by the MAR: system development (better systems and tools), human-robot interaction (better interaction), mechatronics (better machines), perception, navigation and cognition (better action and awareness).

The general objective is to enhance the level of all abilities such as perception and cognitive abilities, decisional autonomy, configurability, adaptability and interaction ability, which make a robot able to operate in unknown or highly uncertain environments, also cooperating with humans, in an efficient and safe way. Research spans numerous applications fields including manufacturing, healthcare, agriculture, civil, transport and logistics, and involves different robot categories from ground to aerial and marine robots.

Perception

Research activities in the context of perception are related to the development of advanced perception systems for ambient awareness of robotic platforms working in dynamic semi-structured and unstructured environments. Main research issues include the design and development of multi-sensor platforms and multi-sensor processing algorithms to be integrated on-board unmanned ground vehicles for tasks, such as multi-modal map building, situation awareness, and traversability estimation\textsuperscript{32}. Alternative sensing modalities like radar, depth-sensors, and cameras sensing outside of the visible spectrum (e.g., thermal cameras or hyperspectral cameras) and their intelligent combination and fusion, have been investigated for autonomous navigation under field conditions\textsuperscript{33}.

Research challenges also deal with the design and development of novel estimation and cooperative perception strategies for robotic networks, integrated with IoT devices, to perform tasks, such as cooperative mapping, cooperative manipulation, target tracking, and environmental monitoring\textsuperscript{34, 35}.

In this respect, a key issue is communication. Joint design approaches have been proposed to combine safety and security requirements in communication networks, in the typical modern scenario of ubiquitous connectivity\textsuperscript{36}. The application of the IoT paradigm in a wider context has been investigated and possible


\textsuperscript{36} Bacco, F.M., Berton, A., Ferro, E., Gennaro, C., Gotta, A., Matteoli, S., Paonessa, F., Ruggeri, M., Viron, G., Zanella, A., “Smart Farming: Opportunities, Challenges and Technology Enablers”, IEEE IoT Vertical and Topical Summit for Agriculture, 8-9 May 2018, Borgo San Luigi in Monteriggioni, Siena (Italy)
technology enablers, from both already available and upcoming standards, have been surveyed. A dedicated service-oriented approach, enabled by high-speed in-vehicle networks, has been devised to manage automated working machines.

**Interaction and Cognitive Ability**

The design of suitable cognitive architectures inspired by human mind represents a promising way to manage complex human-robot interactions. Starting from research activities dealing with natural human-robot interfaces, research at CNR investigates on explicable AI solutions for physical and cognitive interactions. In particular, we explore the detection and recognition of human gestures, the processing of natural language, the knowledge representation by semantic and conceptual spaces. The analysis and evaluation at the various levels of abstraction of the human-robot interaction through cognitive models and architectures aim to enable complex social interactions and effective task cooperation. By detecting, classifying and recognizing the human intentions, emotions, and behaviors, we propose both deterministic and stochastic models for environmental data processing and human understanding. We are investigating on soft-sensors approaches for data fusion, and machine learning methodologies to process the knowledge (e.g., interactive genetic algorithms, artificial neural networks, deep learning architectures). The cognitive architecture proposed and under further development, allow the robot to have sophisticated cognitive capabilities, such as the artificial creativity, the management of social practices, the emotional reacting by an artificial somatosensory system, the verbal and not verbal interactions through social signals.

A main issue in human-robot interaction is safety. Safety of the operators is of utmost importance. In several cases, the physical contact can be established mitigating the risks associated with exceeding energy exchanged in the interaction. This can be performed with a collaborative robot control paradigm, providing a constant and dynamic information flow between the operator and the robot. Moreover a protective safety function, enabling motion or other mechanical parameter limitation have to be provided to the software controlling the system or overall power limitations, in order to immediately stop unexpected movements. Anyway, risk reduction is due to risk assessment and cannot be granted “by construction”.

**Adaptability, Configurability, Decisional Autonomy**

Research activities are concerned with: the design and development of robotic systems able to mimic biological systems in unstructured environments; the design and development of bio-mimetic robotic vehicles combined with novel actuators and sensors able to replicate and improve biological systems; the development of robotic arms capable of mimicking the soft-behavior of human arms. This allows developing bio-inspired robots capable of cooperating in a flexible way without rigid constrains. Biologically inspired techniques have been proposed also for the design of decentralized algorithms for multi-robot and swarm robotics systems. A design pattern methodology has been advanced to provide formal guidelines for the implementation of decentralized controllers that predictably result in desired behaviors. Reinforced random walks have been proposed for wide-area exploration and exploitation of resources, achieving high efficiency, robustness and scalability.

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Pioneering contributions have been given to the theoretical foundation of the open-ended learning robot field\(^{41}\), and to early models based on bio-inspired solutions.\(^{42}\) Important contributions have also been given to the development of robotic architectures and algorithms able to autonomously acquire skills on the basis of the self-generation of goals and tasks.\(^{43, 44}\)

Among artificial intelligence techniques, Automated Planning and Scheduling constitute a research area suitable for addressing intertwined task planning and execution in robotics. Among different approaches, timeline-based planning has been successfully deployed in real-world robotic applications. Timeline-based planning entails the control over time of different logical/physical components and temporal their behaviors (i.e., the timelines) for guaranteeing the achievement of desired goals.\(^{45, 46}\) The integration of such technology with Verification and Validation solutions\(^ {47}\) is fostering also robust control solutions for guaranteeing effectiveness and safety of autonomous robots\(^ {48}\).

Dealing with safe Human Robot Cooperation algorithms and validation methodologies for collaborative modes are needed. Ongoing research activities are setting the ground for model-based assessment of human-robot collaboration and formal verification of risks and associated protection strategies, making use of several industrial use cases in the domain of machine tools and robot handling.

Adaptability and reconfigurability requires standard interfaces to many sensors and robots setup. This can be achieved through shared development within the ROS-I open-source community encapsulating in its ROS-I packages the state of the art of industrial robotics research, and the innovative control architecture. This approach allows a robot-agnostic development also of user-level control strategies (adaptive shaping of the control inputs).

2.2 Control Systems

The activities of the CNR researchers working in systems & control can be catalogued in the following main fields: 1) Control, estimation and optimization, 2) Modeling and identification, 3) Probabilistic methods and uncertain systems, 4) Networks, 5) Plasma structures.

Below a brief description of each field is reported, together with the main adopted methodologies.

**Control, estimation and optimization**

Control, state estimation, and optimization for complex nonlinear systems are fundamental for increasing efficiency. Such processes can be either continuous or discrete in time, and with lumped or distributed parameters. In general, the developed approaches for control and state estimation must ensure robustness, stability, accuracy, optimality and be computationally efficient. Among the main and most significant research activities we cite the following: model predictive control, approximate dynamic programming, 41 Baldassarre, G., & Mirolli, M. (2013). Intrinsically Motivated Learning Systems: An Overview. In: Baldassarre, G., & Mirolli, M. (Eds.), Intrinsically Motivated Learning in Natural and Artificial Systems. Berlin, Springer-Verlag, 1-14.
observer design, nonlinear filtering, moving horizon estimation, functional optimization, neural networks, consensus, robust control, sliding mode, distributed control and estimation.

**Modeling and identification**

Systems modeling and identification play a fundamental role in the design of control systems. In fact, having at disposal an accurate model of a process makes it possible to design effective control techniques that exploit future information and also prevent possible failures. Often, the models are built starting from a few data collected on the field that are affected by disturbances. Among the main activities, we mention the following: parametric identification and black-box modeling, study of the structural properties and solutions of differential systems, positive systems, fault diagnosis, interconnected and distributed systems, multi-agent systems, model building starting from statistical descriptions, systems of systems.

**Probabilistic methods and uncertain systems**

Probabilistic and randomized methods have been developed as effective tools to deal with uncertain complex systems. The starting point is the assumption that uncertainty is described in a stochastic manner, and the goal is to provide probabilistic assessments of system performance. In this context, we accept the risk that a certain property of the system is violated with low probability. Such systems can be seen as “practically robust” from a technological point of view. One of the advantages of these methods is to provide a link between stochastic and robust methods, using innovative concepts such as the probabilistic robustness margin and the probability degradation function.

**Networks**

In recent years, the theme “networks” has become central in the research area of control systems. Networks represent a research activity that includes several applications of interest, such as the rapid spread of financial crises and epidemics, the aggregation of human behavior, and the development of the Internet. More specifically, crucial research are the study of consensus and the coordination of multi-agent systems through a graph-based approach. Significant results have been achieved in contexts such as social networks, synchronization of wireless sensor networks, development of robotic networks using distributed algorithms, and control systems over non-ideal communication networks.

**Plasma control**

In the context of nuclear fusion plasma control, the main contributions are the integrated modeling of plasma and active or passive conducting structures, system parameter estimation, control algorithms and optimization, complex system analysis, distributed control systems, fast (sub ms cycle-time) computer-based, real-time applications for feedback and feedforward control, network-based applications, human machine interface, and graphical user interface applications.

**3. IMPACT**

**3.1 Robotics**

The impact of the research carried out at CNR in the robotics area is manifold. In particular, the development of advanced perception systems also using alternative sensing modalities is fundamental to enhance the autonomy and safety level of robotic platforms operating in key sectors such as agriculture (i.e., development of highly automated vehicles and machines for precision farming applications), manufacturing (i.e., process control, surveillance and security) and transport (i.e., autonomous vehicles and advanced driver-assistance systems). A large impact is expected by research in multi-robot systems, as many application domains can benefit from parallel task execution and collaboration among robots. Additionally, the flexibility and robustness featured by swarm robotics approaches is key in several field applications. One such field is agriculture, where automation and precise interventions can result in reduced inputs, large costs savings and improved yield.
Regarding open-ended learning, important applications are in the field of service-robots where robust and versatile behaviors, and variety of solutions, are more important than accuracy. The developed techniques for autonomously-learning robots can especially benefit the applications that require robots to act in real-life unstructured environments posing challenges unexpected at design time.

Timeline-based planning, dynamic task planning and coordination issues constitute key enabling technologies for the development of decisional autonomy solutions for robotics in human-robot collaborative scenarios. Cognitive interactive robots could enable effective social interactions between humans and robots that are necessary for real contexts. The scientific outcomes could be useful both in robotics to extend the range of application outside the typical context of the factory, and cognitive science to develop a new model of representing human behaviors and managing complex interactions. At social level, social robots could give different supports, from the execution of repetitive or dangerous tasks to the affect-based involvement to improve the quality of the human life in a domestic environment. Cognitive robots could give an impressive enhancement of a smart learning environment, or assure innovative health applications both in medical and home environments. The fruition of cultural heritage sites, and in general of public and commercial spaces are other very interesting domains of cognitive, social robotics applications that in future could have a relevant impact. New enhanced robotic systems that are also capable of enhancing the knowledge of nature will improve everyday life systems, e.g., by integrating biological principles with engineering knowledge. Furthermore, a control paradigm can improve safety in the use of robotic system in several critical environments, and in particular in all the human-robot collaborative operations, thus facilitating the use of these systems in several fields (surgical rooms, care giving, etc.)

CNR substantially contributed to the standardization of robot safety, furthermore offering expertise and support to the industrial community in designing and verifying collaborative applications. CNR is an active member of several standardization committees, and major initiatives for engaging stakeholders in robot safety and for supporting the community in deploying collaborative applications in more cost-efficient way (see H2020 FSTP-type Project “COVR”).

The adoption of open source approaches in the development of innovative solutions aim at providing advanced tool to industry very easy to be used and with low-cost of ownership (FOSS business models), boosting and supporting the creation of high-skilled workers in the factory.

When the full enablement of autonomous machines is completed, both on the technological and regulation side, a major breakthrough is expected in our society, with people being removed from repetitive, unhealthy and dangerous tasks and benefitting from the services of evolved artificial assistants.

3.2 Control Systems

The research in control systems has a long history, which involves and allows the automation of industrial processes, thus improving the overall efficiency of equipment and processes. Current research trends focus on large-scale interconnected systems and on the optimization of processes within them, for which a multidisciplinary approach is fundamental. The results of the research have enormous potential to make industrial processes flexible, resource efficient, and to a certain extent self-aware.

CNR conducts research in control systems in line with these trends and actively contributes by publishing cutting-edge research and creating innovations with industrial partners. The area concerning Intelligent Industrial Processes is a multidisciplinary research and innovation area related to Process Industrial Automation. Automatic Control is also considered a key enabling technology for the realization of future visions and ambitions in emerging areas such as biomedicine, renewable energy, and critical infrastructures. The increasing complexity of technological systems requires multidisciplinary research and development. Toward this end, it is worth noting that collaborations between control systems and other fields have always been fruitful.

CNR has a solid research experience in close collaboration with process industries: research results have often resulted in products and services and thus reinforced the position of industries on the market. Current research activities in Automatic Control at CNR are very relevant for Intelligent Industrial Processes, dealing with techniques such as process understanding (modeling), design and implementation of control systems, and process monitoring. Collaborative and multidisciplinary research in this area is essential and enables industrial partners to work more efficiently with their industrial processes and in close collaboration with researchers and engineering firms. At the same time, researchers have the opportunity to test and validate their results and innovations on real cases, allowing rapid exploitation of results.

For instance, CNR is at the leading edge of several systems and control applications: (i) design of guidance and navigation schemes for rendezvous and docking maneuvers of spacecraft (in collaboration with DIMEAS Polito), (ii) modeling and design of innovative architectures for UAV indoor navigation (DIMEAS), (iii) design of control architectures for modern agricultural robotics using both UAVs and AGVs (DISAFA Unito), (iv) fast real-time control of plasma MHD modes and plasma parameters, (v) analysis of techno-social networks, with focus on the influence structures in Italian Parliament (with OpenPolis).

4. EMERGING RESEARCH CHALLENGES

CNR Institutes pertaining to the Robotics and Control Systems area have complementary competences ranging from system and control engineering, to computer science and artificial intelligence, which can be usefully integrated to address emerging challenges and contribute significant advances in the field.

Cooperation will take place through initiatives such as organization of workshops and meetings, and presentation of joint research and development projects within national and international programs.

In the robotics area, emerging research challenges are manifold. In terms of Key Technology Clusters, they can be resumed as follows:

- **Perception, navigation and cognition**: perception systems are fundamental for the robot to achieve a clear understanding of the environment and successfully accomplish its tasks with limited human supervision also in long-duration and long-range operations though preserving safety. CNR plans to address this challenge by developing multi-sensor platforms and multi-sensor processing algorithms also using alternative sensing techniques to increase the capability of the robot to operate under variable environmental conditions. Emerging challenges in the context of multi-robot systems will be addressed. MRS are key for increased automation (e.g., autonomous cars, UAV swarms), contributing to improve working conditions and promoting sustainable development (e.g., precision agriculture, logistics). In the context of cognition, the field of open-ended learning robots has recently received a strong attention from the deep neural-network and deep reinforcement-learning community as these techniques have a great potential to benefit autonomous learning in robots. CNR plans to address this challenge by exploiting the potentialities of these techniques to implement some components, embedded in the developed open-ended learning robot architectures, that undergo the most challenging learning processes. Another emerging challenge is related to the integration of semantic technologies and automated planning and scheduling techniques to define a high-level control level that reproduces a (virtual) abstraction of information gathered from sensorised robots (and the environments in which operate) for evaluating, configuring and tuning tailored control functions over time.

- **Human-robot interaction**: an important research challenge related to timeline-based planning and execution is related to safety issues maintaining effective collaboration for HRI scenarios. HRI issues include also multi-modal communication between the robot and the human, as well as the sensibleness of robotic behaviors. The long-term goal is the definition of a symbiotic framework in which humans and robots can effectively collaborate for a shared goal preserving human safety. Another research challenge deals with the investigation of the effects on human behavior (errors, voluntary/accidental reactions, etc) for mid/long-term risk evaluation and analysis of hazardous
patterns. This challenge calls for the development of methods and tools for Computer-aided Risk Assessment and self-validation functions, able to automatically analyze a robot system along different applications or changes in behavior or components. Challenges are also related to the development of robots equipped with a suitable cognitive architecture, which could make effective the long-term human-robot interactions, collaborations, and social supports.

- **System development:** Advanced robot architectures (for example, mixed series and parallel elastic actuators, exoskeleton) required advanced control algorithms, like fractional-order and model-predictive controllers, to ensure robustness and performance while respecting the constraints. The controller will manage data coming from many different sensors, while it will provide information on the robot system status to the rest of the net. These advanced controllers will require realistic simulations. For this reason, robotic cell modeling and identification should become user-friendly tools hiding their complexity by means of fully automated identification experiments. Learning algorithms will be expensively used to properly tune the algorithm without required advanced user’s know-how. Moreover, the motion planning represents a key aspect in un-/semi-structured environments. In this field, massive parallel computing could strongly reduce the computational time of collision detection and path planning. In particular, heuristic based algorithm (namely, RRT-based algorithms, ant-colony optimization, particle swarm algorithms). This will increase the robot promptness. Moreover, the increasing complexity and flexibility of robotic cells, characterized by a large number of sensors and robot working together, require standardization and modularity. Robotic operating system (ROS), and in particular the ROS-industrial consortium, is a rising platform in industrial and mobile robots. The main activity in this field is related to develop industrial-oriented packages and to guarantee uniform support. In particular, more reliable motion planning algorithm for industrial scenarios, plug-and-play modeling-to-control packages, and simple device integrations and abstraction. Additional emerging challenges concern the design, development, and control of soft-robotics and soft grippers to increase manipulability; improving the operational safety of the systems, through collaboration with end users, so as to design flexible and attractive/useful devices supporting and facilitating human operations.

Research on control systems is quite mature, but a number of research challenges still need to be faced. Examples are the development of algorithms well suited to being applied for large-scale, distributed, and decentralized systems, together with the study of novel application fields aimed at increasing well-being of humans, such as biomedicine, biology, and reduction of pollutant emissions.

5. CONCLUSIONS

Robotic and control systems are becoming more and more ubiquitous in many application fields such as manufacturing, healthcare, agriculture, civil, commercial and consumer, transport and logistics, experimental devices for physics research. This document provides a review of the state of the art and research challenges in the field, including open issues, needs and future trends. Robotics and Control Systems constitute a huge scientific area and this review is therefore not intended to be comprehensive, but rather focused on the main recent and current research activities carried out at CNR and their positioning and impact in the relevant area.

With specific reference to Robotics, research activities include AI and innovative hardware solutions for wearable robotics and human-robot interaction, exoskeletons and bio-inspired cognitive architectures, open-ended learning, soft-robotics solutions, design and development of advanced perception systems, multi-robot systems, IoT-Robotics and communication networks. The general objective is that of enhancing all robot abilities, as defined by the MAR, to develop robotic platforms able to operate safely and effectively in uncertain and variable contexts, also in the presence of humans.

Research in control systems at CNR is aimed to study complex systems, possibly interconnected, nonlinear, and dependent on a large number of parameters. Major challenges include the development of algorithms well suited to be applied for large-scale, distributed, and decentralized systems, together with the study of...
novel application fields aimed at increasing the well-being of humans, such as biomedicine, biology, reduction of pollutant emissions, etc.

CNR Institutes in the Robotics and Control Systems area have complementary competences ranging from system and control engineering, to computer science and artificial intelligence, which can be usefully exploited and integrated to address emerging research challenges. CNR is an active member of several standardization committees, scientific associations, clusters, competence centers, and major initiatives for engaging stakeholders and for supporting the community towards the development and deployment of innovative robotic and control systems in their diverse application fields.
EXECUTIVE SUMMARY

This white-paper reflects the CNR vision of the Factory of the Future and is conceived to provide a reference model to support the transformation of National and European manufacturing sectors, which need to undergo innovation-driven evolutions to maintain competitiveness while facing mega-challenges, such as globalization, resource scarcity in the global knowledge society. It collects the contribution of all the CNR Institutes working on this thematic area, namely: IEIIT, IASI, IMEM, ICAR, ISTI, IMATI, ISTC, IMAMOTER, IIT, IAC, IFAC; IREA, STIIMA.

1. STATE OF THE ART OF THE RELEVANT SCIENTIFIC AREA

The Manufacturing sector is a fundamental pillar for the technological progress and the economic and social prosperity of modern countries. Italy plays a primary role in Europe and can rely upon unique resources to preserve and enhance its competitiveness in manufacturing. In Italy, the manufacturing sector includes 427 thousand companies employing around 4 million people, generating a turnover of 871 billion euro and an added value of about 225 billion, ranking in sixth place in the world rankings for the weight of the sector in the economy. It should be noted that among the top ten European Manufacturing Regions by number of employees and number of companies, there are four Italian Regions: Lombardy, Emilia Romagna, Veneto and Piedmont.

Italy concretely represents a set of optimal environmental conditions difficultly replicable in other contexts, as its industrial vocation, the ability to create products that combine design, technology, personalization and thanks to the great tradition in the machinery and automation sectors. Representing a reference point means for the CNR to successfully conduct research and innovation that leads to the enhancement of the sectors in which the country can best express its potential.

In the Manufacturing field, the Factory represents the reference paradigm and therefore it makes sense to develop activities oriented to the evolution of this paradigm in which different enabling technologies also linked to the digitalization of manufacturing are proposed as a way for innovation. The role of IoT (Internet of Things) tools, Cyber-Physical Systems (CPS), digital manufacturing, big data analytics, advanced sensors and intelligent sensor networks is crucial to improve the efficiency and sustainability of products, processes and production systems, towards a circular economy vision. Industry 4.0 is the next developmental stage in the organisation of the manufacturing value chain, with ICT-based systems playing a major role, mainly by creating a virtual copy of the physical world and facilitating decentralised structures through cooperating CPS.

At the same time, the required industrial evolution must run along different lines that are complementary to each other such as: advanced production technologies; mechatronic systems; systems for the integrated modeling and simulation of products and processes; technologies for product customization, for the enhancement of people in factories, for environmental sustainability, for the management of the product End of Life (EoL), for the development of innovative materials and for the strategies and management of new production processes.

In this context, the driving aspects in the development of the aforementioned enabling technologies for the Factory of the Future are: the implementation of digital technologies, the adoption of both a technology push-market pull approach, the definition of open and participatory standards taking into account the specific Italian context mainly characterized by small and medium-sized companies, the focus of digital technologies towards the strategies for the circular economy and for product customization as well as the centrality of man in manufacturing production processes.
The role of the CNR in supporting the Italian manufacturing sector has been explained over the years by promoting research and innovation with participation in significant initiatives both at Italian and at European level.

2. CONTRIBUTION TO THE RELEVANT SCIENTIFIC AREA

The main activities of the CNR’s Institutes on the topics are described in the following, as well as the main involved Institutes. Such activities span over all the main industrial sectors (fashion goods, machinery, construction, agricultural machinery, food, automotive, aeronautic,...).

1. **Systems for personalised production**

The main research and innovation topics are related to different aspects of product development, including products to enhance consumer’s health and well-being, towards the development of solutions and systems for the efficient production of personalized products with high added value, in order to promote the growth of the Made in Italy paradigm in Europe and worldwide. These systems should support a fast ramp-up and short configuration and re-configuration time to satisfy custom requirements, guaranteeing a high level of integration with clients and client specifications, and they will be characterized by new business models and agile and flexible supply chains.

In order to meet the increasing demand for product differentiation and customisation in terms of advanced features and smartness, the personalised production paradigm is shifting toward the adoption of novel technological approaches, such as hybrid processes and additive manufacturing. The combination of advanced manufacturing technologies with innovative approaches to the process monitoring and control, along with ICT solutions for the acquisition of the client’s requirements, product configurators, advanced measuring systems, is leading to the development of new flexible and agile manufacturing models considering product modularization strategies, postponement and multi-decoupling points. The main addressed research topics are:

1.1 Innovative methodologies for product analysis and design
1.2 Digital Manufacturing tools and systems for Computational Design & Engineering, including methods for the integration of Computational Aided Design & Engineering
1.4 Process Planning for Additive Manufacturing
1.5 Advanced tools for the configuration and design of personalised solutions
1.6 Technologies for personalised production with high added value
1.7 Mini-factories. A model for re-organising the production and distribution chain.

2. **Strategies, methods and tools for industrial sustainability**

To respond to the growing complexity and competitiveness of the industrial scenario, new models and solutions have to be designed and developed, to improve both product and process sustainability, considering its whole life cycle and the future evolution of needs and availability of resources.

To tackle this challenge, new product and process design solutions are required, technologies and machine tools need to be improved, as well as an improvement in energy efficiency and waste reduction. They should be part of a more broader approach based on circular economy, with closed supply chains and coherent business models, exploiting all the knowledge-based tools and methodologies offered by the smart factory paradigm. The industrial actors should share information through the integration of machines, operators and factories, in order to improve their flexibility, reconfigurability and reactivity to the more and more dynamic requests of the markets.

The main research lines within this topic are:
2.1 Methods, tools and KPIs for the sustainability of the production activities
2.2 Methods for the analysis and the improvement of the sustainability of the extended factory
2.3 Technological solutions to improve energy efficiency and reduce waste
2.4 Innovative products
2.5 Methods and integrated tools for eco-design
2.6 Methods and tools for de-manufacturing systems with improved flexibility and their supply chains.
2.7 New business models and sustainable value chains

3. Human centered factories

Based on the specific challenge arising from the demographic and social trends and the needs of all categories of workers, the research activities are focused on the design and development of production systems that can host people and enhance their skills in order to give a contribution to the satisfaction and well-being of workers. Indeed, the factory of the future will increasingly face problems linked to ageing population that, reflecting itself in an extension of the working life, makes it necessary to enable people to carry out their job compatibly with the evolution and change of their cognitive and physical abilities. Addressing this issue requires a huge effort from both technological and organizational point of views. Therefore, the innovative factories will have to be increasingly inclusive, or strongly oriented to the involvement and participation of people (users, operators, managers) who will perform complex activities with high added value with the support of innovative tools and devices. As a result, people and machines will have to be able to cooperate synergistically, sharing activities in an efficient and safe way. The workplace will have to be redesigned on the basis of specific rules of ergonomics and organized according to adaptive work rhythms to provide an environment and working conditions appropriate to the different people, in order to allow them to operate productively regardless of their age, sex and physiological or pathological status. Similarly, the use of enabling technologies aimed at the digital representation of the factory promotes the integration at information and knowledge level. Hence, each person has to be considered a central element with respect to all the levels and dimensions defining the factory. In a context characterized by factories where products, processes and technologies evolve through articulated dynamics, a fundamental challenge is represented by the knowledge and the ability to interpret complex production phenomena and identify solutions based on experience. Therefore, it is essential to invest strategically also in the enabling technologies, such as VR/AR to support to support user-centered tasks such as operator training and maintenance support by means of visual, auditory, tactile feedback and interaction, as well as appropriate semantic and ontological representations of information and knowledge to support the formalization and reuse of such experiences.

Specific research topics are:

3.1 Innovative devices, systems and strategies for online security monitoring
3.2 Cyber Physical Systems (CPS) for safety and security in the Factory of the Future
3.3 Human-Computer Interaction (HCI) devices, tools and methodologies to manage context dependent information in production environments
3.4 Methodologies for ergonomical assessment and optimization
3.5 Tools for worker activities analysis
3.6 Innovative mechatronic devices – hardware, control architecture and sensors- for safe human-robot cooperation
4. **High efficiency adaptive and evolutionary production systems**

The research topic aims at developing both high efficiency production systems to minimize production costs and consumption of resources and energy, while improving productivity and product quality and a new generation of evolutionary production systems dynamically adaptable to the external changing conditions, due to the fast evolution of technological processes and the frequent and sudden changes in demand, in terms of production mix and volumes required.

To achieve the abovementioned goal, several topics need to be addressed:

4.1 Advanced control systems and real-time optimization for production lines and systems: design and development of self-optimizing control systems in real time, through the adoption and extension of predictive and model-based control techniques on distributed architectures (DMPC), development of dynamic real-time optimization (DRTO), integration of hybrid control systems including decisions of a discrete and energy-aware nature, dynamic identification techniques for the optimization of distributed systems and industrial Cyber Physical Systems (CPS).

4.2 Industrial communication systems: high performance industrial wireless networks, Clock Synchronization Protocols, real time Ethernet, Modbus, CAN, CAN FD.

4.3 Formal Methods and Models for the Security of Industrial, Cyber Physical and Safety Critical Systems

4.4 Smart components, sensors and machines for adaptive and evolutive production: sensors (eg: x-ray detectors, magnetic based sensors and transducers), Real-time operating systems for multicore processors, real-time multicore scheduling and synchronization and resource management, monitoring, intelligent vision systems for quality control

4.5 Innovative production processes:

4.6 ICT Technologies for the interoperability, agility and servitization of the Factory of the Future: service-oriented architectures, interoperability, optimization methods for the extended factory, for the efficient and collaborative planning and scheduling of global production networks and their supply chains.

3. **IMPACT**

The Manufacturing sector significantly contributes to address the ‘grand challenges’ of the 21st century, promoting a smart, sustainable and inclusive growth, ultimately impacting on employment, wealth, health and ageing population. The manufacturing sector generates about 16% of European GDP and employs 20% of the population (30 million people in 230,000 companies, most of them small and medium-sized). Moreover, the industry supports the service sector. Not only it produces products and goods, necessary for its operation, but it also generates jobs in this sector thanks to the indirect employment (it is estimated that each job in the manufacturing industry generates the double in the service sector). In the European economy and also in the national one, the manufacturing sector represents the first sector for export (being responsible for more than 80% of European exports), it is the first sector for private investments in R&D (66%) [EFFRA], level of innovation and productivity growth.

Specifically, the Italian manufacturing sector generates a turnover of 871 billion euro and an added value of about 225 billion, ranking in sixth place in the world rankings for the weight of the sector in the economy.

For this reason, all countries interested in playing a leading role on the international scene and aiming at industrial independence have to invest in this sector. To accomplish this goal each country should address strategically its manufacturing activities according to its own resources and to the competitive dynamics which determine the international context.

The current international context is characterized by the growth of emerging economies, mostly Asiatic, which are able to offer products characterized by an increasing quality at a lower price compared to the one realized by mature economies. This is made possible by low labour costs, worse working conditions, by the
availability of raw materials and by fewer environmental safety and IPRs regulations. Mature economies are therefore focusing their offer more and more on innovative technologies, personalized solutions, high added-value manufacturing, integrated product-process-system solutions.

In Italy, the manufacturing sector includes 427 thousand companies employing around 4 million people. It should be noted that among the top ten European Manufacturing Regions by number of employees and number of companies, there are four Italian Regions: Lombardy, Emilia Romagna, Veneto and Piedmont.

For each country, research is crucial to address its societal challenges and to successfully follow the innovation path leading to the valorisation of the sectors where the country can best express its potential. Therefore, considering the Italian and European manufacturing sector the following research and innovation priorities seem to be fundamental:

- a new systemic perspective on manufacturing, which considers the coevolution of products processes and systems;
- new cutting-edge technologies and processes to achieve high performance manufacturing (high quality and productivity);
- new advanced manufacturing systems supply chains and business models adaptive and highly integrated, to foster economic sustainability in the various manufacturing sectors in continuous evolution;
- new manufacturing technologies and systems to realize new products for the societal challenges;
- new technologies and solutions to valorise the central role of people and their unique competences;
- new approaches to guarantee a continuous improvement and innovation of the competences of the manufacturing;
- new technologies and solutions for the environmental sustainability of factories, which must use planet resources efficiently within a new manufacturing/de-manufacturing paradigm;
- new ways to effectively and efficiently integrate research and innovation.

In order to drive the change toward the most relevant priorities, it is necessary to lead strategically the research and innovation carried out by universities, research institutions, companies and other innovation actors in order to address them towards innovation goals and policies in an efficient and synergic way. It becomes therefore important for the research and industrial actors, as experts in frontier innovation and technologies, to take an active part in the road-mapping activities and in the definition of the research policies.

The role of the CNR in supporting the Italian manufacturing sector has been explained over the years by promoting research and innovation with participation in significant initiatives both at Italian and at European level such as:

- The launch of the “Manufuture” platform as an initiative to support the manufacturing sector at European level and participation in the High-Level Group of the platform itself;
- The guiding role in the establishment of EFFRA, the Public Private Partnership created by the European Commission on the manufacturing sector, and the definition of the roadmap and the Factories of the Future tenders activated within the relevant European framework;
- The central role in the establishment and growth of the Smart Factory Cluster within the national cluster promoted by MIUR, and the definition of the roadmap for companies in the Italian manufacturing sector, followed by the establishment of 7 working groups on strategic lines of intervention. Participation in cluster projects with a total value of 40 million euros.
- The direction of the “Fabbrica del Futuro” flag project, with important research initiatives aimed at increasing the competitiveness of Italian industry and in particular of "Made in Italy" in the global context. The project has a 12-millions euro loan and has involved CNR institutes, universities, research bodies and consortia, companies and consortia of companies.
- Coordination of the European LET’S2014 conference (Leading enabling Industrial technologies for European Renaissance), promoted by MIUR and MISE, which highlighted the most recent
developments in terms of technologies enabling manufacturing and which represented a key event of the Italian Presidency semester.

- Coordination of the project "Innovative technologies and systems for the factory of the future and Made in Italy" which aims to promote the development of enabling technologies to increase the impact of innovative manufacturing solutions developed in recent international research projects, in optic of synergy and complementarity with the other national initiatives on newly launched manufacturing research.
- Participation in regional initiatives to support manufacturing, including the regional Lombard cluster AFIL with support activities for the definition of strategic lines for research and innovation.
- The direct participation of CNR Institutes in several dozen European research projects in the FOF (Factories of the Future), Robotics2020, SPIRE calls with the production of important industrial results in various technological areas.
- The coordination of the KIC EVCE proposal on Added Value Manufacturing

All these actions highlight the role of the CNR as a primary actor in the initiatives concerning manufacturing in the national and international scene. And they form the basis for defining the goals and objectives of this AP.

4. EMERGING RESEARCH CHALLENGES

The main emerging research challenges address the development of technological approaches merging materials, manufacturing, electronics and AI for the creation of new products, sensor fusion and integration of ICT and analytics to extract information from heterogeneous data sources.

5. CONCLUSIONS

The main objective of the “AP-Factory of the Future” is to expand and to promote research in the manufacturing industry and to represent a research hub in relation to the industrial world. The AP organizes research themes around the concept of Factory, allowing it to be dealt with a pervasive and unitary way all the salient aspects involved. The factory is defined as the coherent set of enabling technologies, processes and products that dynamically evolve over time to follow market needs and new production logic.

Within the organization of research topics, the definition of the main areas of strategic expertise that can contribute to the scientific-technological growth of the manufacturing industry, bringing the research world closer to the industrial needs, is also of significant importance. Most of the projects presented in the previous paragraph are organised to cope with this mission.

The research activities are aggregated in four main area:

1. Systems for personalised production
2. Strategies, methods and tools for industrial sustainability
3. Human centred factories
4. High efficiency adaptive and evolutionary production systems

In order to facilitate the identification of these areas of expertise, it has been associated a series of characteristics that are fundamental for the idea of factory of the future.

1. Intelligent and adaptive: in order to interpret the information and implement autonomously adaptive and repair strategies, modifying its performance, its methods and operating dynamics, in various production fields.
2. Sustainable along its life cycle: operating in full compliance with energy consumption and emissions constraints, as well as from an economic and social point of view
3. Built around people: being strongly oriented towards the involvement and participation of people at various level who can perform complex activities with high added value with the support of innovative tools and devices.

4. Evolutive compared to products-processes: for coping with rapidly evolving demand and production and de-production technologies enabling the reaction to product and process change over time.
AP8 HEALTH CARE AND WELL-BEING

EXECUTIVE SUMMARY

AP HWB focuses on the design, development and evaluation of ICT and engineering solutions for diagnosis and therapy in medicine, empowering citizens towards healthier life styles and preventing or managing chronic conditions. To this aim, it applies engineering design and analysis principles to biological systems and biomedical technologies.

In the last few years, as part of the preparation of the forthcoming Horizon Europe, AP HWB research mainly focused on two keystones: personalized medicine and digital transformation.

Personalized medicine has been defined by the Horizon 2020 Advisory Group as "a medical model using characterization of individual phenotypes and genotypes (e.g. molecular profiling, medical imaging, lifestyle data) to tailor the right therapeutic strategy for the right person at the right time, and/or to determine the predisposition to disease and/or to deliver timely and targeted prevention”.

Digital transformation of health and care process strongly supports this vision by providing important instruments to exploit innovative ICT solutions in terms of advanced devices and systems, high performance computing, data analytics and artificial intelligence to help design and test new healthcare products, provide faster diagnosis and better treatments.

Together with these two keystones, other issues have been identified at international level as those on which the research in health engineering must invest in the near future. Among them, one can find service robotics, technologies for health and environment protection, modelling and computational approach to medicine, tools and equipment necessary for the advancement of diagnosis and therapy, and technologies for the management of health systems.

AP HWB is aligned with this trend by studying, designing and developing tools, technologies, devices and services at the cutting edge of the knowledge, able to effectively implement the 4P paradigm: a Predictive, Preventive, Personalized and Participatory medicine.

This document presents the current activities of AP HWB, divided into 7 pillars fully in line with the priorities identified at European level:

- Digital solutions for health throughout the life course (DIGHEALTH)
- Service robotics (S-ROB)
- Environmental and social health (ENVHEALTH)
- In silico models for health (MODEL-H)
- Tools, technologies and devices for advanced diagnosis and therapies (HTECH)
- Tools for personalised medicine (T-PERMED)
- e-Health and health care systems (E-HEALTH)

After a short description of the state of the art of each pillar, the current activities of AP HWB will be described, together with their impact and the identification of the specific challenges of the next future. The description of CNR effort in terms of personnel, active projects, available infrastructures and facilities are described in the annex.

1. STATE OF THE ART OF THE RELEVANT SCIENTIFIC AREA

DIGHEALTH

One of the main focus of H2020 SC1 is to support ageing populations and the increasing number of subjects affected by multiple chronic and/or degenerative diseases by promoting innovative solutions for active and healthy aging, able to assist people in their living environments. In the last few years, also an increasing
interest is emerged in solutions able to address other vulnerable stages of life, like childhood and adolescence, including people with disabilities or specific health needs. In this case, the definition of personalised solutions able to promote healthy life styles and social inclusion, even from the early stages of life, can help reduce the risk of mental and physical diseases later. Solutions originally developed for health monitoring and support of elderly can be further improved and customised for different user categories and pathologies, also enabling the integration of different solutions, including self-monitoring and Ambient Assisted Living (AAL), in order to provide a complete analysis of the health status of each subject. In addition, those solutions should be developed on scalable, re-usable and adaptive architectures, be interoperable and concretely evaluated in real-world scenarios.

**S-ROB**

The European Commission is investing in Robotics as one potential technology that could transform health care in the coming years. In particular, service robotics are being developed, tested and implemented in order to enable novel rehabilitation and surgical procedures, to assist impaired people in performing tasks of daily life, to encourage social interactions and active and healthy ageing. The 2020 Multi-Annual Roadmap (MAR) for Robotics in Europe identifies the Assisted Living sub-domain as the one addressing robotic solutions and technologies that aim to improve the quality of life by enriching the environments where humans live and work. These new technologies need to provide end-users, especially older adults, with dependable, acceptable and sustainable support and assistance including, where necessary, individually tailored systems.

**ENVHEALTH**

Human health is closely linked to the quality of the environment, as it is influenced by the interaction between environmental conditions and biological systems. This interaction is extremely complex to be understood, varying not only in relation to the physical agent to which an organism is exposed but also to the characteristics of the agent itself. The knowledge of interaction plays a crucial role in the assessment of the possible health risks due to exposure of the population. Additionally, there is a need to contextualize health data from patients as a function of the environment, to better assess the risk of diseases and the health at large.

**MODEL-H**

In medicine, the natural extension of in vitro and in-vivo experimentation is represented by in-silico modeling, in which physical-mathematical models are used to understand physiological and pathological processes, to define and evaluate the diagnostic pathways and their effectiveness, including pharmacological processes. The prime mover of their diffusion and enormous use is certainly the explosive increase of computing power at continuously decreasing costs, which allows the implementation of computational models unimaginable until a few years ago. The in-silico models allow the evaluation of systems and processes of a virtually unlimited number of parameters and possible conditions, finding in biomedical applications a fertile and exponentially growing field. Only through this approach it has been possible to come to an understanding of previously unknown physiological and pathological mechanisms in all sectors of medicine, to design and develop medical devices and technologies that not only prolong life but significantly improve quality, create sensory, motor and cardiovascular prostheses, implement oncological models able to give fundamental answers for the development of therapies and diagnostic approaches, modeling entire organs and systems. Last but not least, in silico models play a key role in computational planning tools for personalized treatments.
**HTECH**

Engineering for health, by exploiting all the most innovative available techniques and technologies, is called to design, develop and implement tools and devices achieving previously unimaginable progresses in diagnosis and therapies.

Innovative biomedical applications of electromagnetic fields (EMF), the increasing interest in magnetic nanoparticles and multifunctional nanocomposites, which enable multiple selective therapeutic and diagnostic approaches, contrast enhanced microwave imaging and thermally induced drug delivery are among the evidences of this innovation process. Formulation of a rapid diagnosis and identification of the most suitable therapy are made available by Point of Care Testing (POCT) devices, able to monitor bioanalytes at the patient’s bed. Plasma medicine, by using low-temperature, atmospheric pressure plasma, interacts with living matter in cancer treatment, non-thermal blood coagulation and transfection of genetic material.

**T-PERMED**

The nowadays availability of complex, very large and high-dimensional datasets, coupled with the last advances in artificial intelligence tools, from network analysis and machine/deep learning to statistics and graph theory algorithms, is pushing the transition toward Personalized Medicine. Even though this novel paradigm is promising virtually infinite possibilities for advancing healthcare systems, some aspects still need to be tackled for its concrete realization. First, effective techniques to interpret and correlate vast amounts of heterogeneous data (from biomedical 2D/3D images and signals until omics, radiomics, connectomics and epigenetics data and clinical documents), need to be devised and tailored, allowing comparative analysis among known or similar cases and statistical analysis over significantly large populations. Second, advanced algorithms to mine, from this information, explainable predictive models for treatment, diagnosis and prevention of diseases of different specialties need to be realized. Finally, solutions to enable physical or virtual interactions with patients/doctors in supporting and monitoring daily care activities have to be developed.

**E-HEALTH**

One of the main priorities of European governments is to make health systems easily accessible, interoperable, secure and trusted, especially with respect to health information and personal data. Indeed, the integration of the large amounts of valuable health data, generated and collected during citizens’ medical examinations in different clinical settings, offers enormous possibilities of reuse for research and better care purposes. To this aim, several national and European ICT systems have been realized to support exchange and analysis of huge amount of health data produced daily by clinical organizations, employing health standards, coding systems and medical terminologies. However, the partial and often trivial adherence of native data, typically stored in silos, to syntactic and semantic standards, as well as the heterogeneity of health processes and security measures, represent open and challenging problems not solved yet.

2. **CONTRIBUTION TO THE RELEVANT SCIENTIFIC AREA**

**DIGHEALTH (IFAC, IIT, ISTI, ISTC, STIMA)**

Consolidated expertise in personalized and self-monitoring solutions, based on remote monitoring, m-health and AAL. Specifically, on: (i) scale-up and integration of IoT platforms for smart environments; (ii) multi-dimensional, personalized coaching system and persuasive technologies to stimulate and empower citizens towards healthier life style and prevent physical and cognitive decline; (iii) personalised services for remote and self-monitoring. This generates a big amount of real-world data to be collected, related to daily activities, physiological data, social interactions, dietary habits, motor and cognitive behaviour of each subject. The integration and analysis of this data on medium and long-term monitoring sessions allow the detection of
anomalous behaviour, possible physical and cognitive decline, stress conditions and to prevent high risk situations, especially in chronic conditions and multi-morbidities.

Development and scale-up of those technological solutions and on the integration and analysis of real-world data to provide personalised suggestions and promote healthier life styles, study of big data analytics tools to provide a territorial observatory of societal well-being.

Study and implementation of cyber security methodologies and techniques (defined in the CyberSecurity AP) for the management of personal health data, with particular reference to the new General Data Protection Regulation (EU 2016/679). These techniques are also common to all the other activities described below.

**S-ROB (IEIIT, ISTC, STIMA)**

Service Robotics is aimed at integrating smart assistive environments with robotic solutions to help humans. This entails many research efforts in terms of: i) development of sensor networks and semantic interpretation of the gathered data; ii) deployment of robotic solutions able to guarantee safety, reliability, robustness and flexibility; iii) design and implementation of advanced models of Human-Robot Interaction conceived to foster a high positive perception of care presence for the older users; iv) design of user models that allows to build personalized services; v) customization for different scenarios like private homes and public health facilities; vi) continuous self-adaptation of services; vii) user experience evaluation.

Development of robotics solutions for rehabilitation, exploitation of new artificial intelligent algorithms, (immersive) virtual and augmented reality applications, quantitative methods for the evaluation of patients and therapy effectiveness, manufacturing of personalized components by additive manufacturing technologies. These activities are based on economic sustainability and ease of use, to exploit solutions also in non-clinical environments, reduce hospitalization and improve the autonomy in the activities of daily living.

**ENVHEALTH (IAC, IEIIT, IFAC, IREA, IMEM)**

Development and use of methodologies for the human exposure evaluation: i) measurement environmental campaigns in public and private workplaces; ii) definition of standardized methods of assessment, design of ad hoc instrument chains and development of adequate measurement and data processing procedures; iii) development and use of specialized software for EMF numerical dosimetry; iv) development and use of EMF stochastic dosimetry; v) in-vitro study of the possible induced biological effects for the evaluation of interaction mechanisms with biological systems.

Improving health information and data exploitation by integrating clinical records coming from medical history data and molecular data (including omic-data) in a novel platform, which enables (in respect of the privacy) to geo-referencing all patient data and integrate it with heterogeneous information.

**MODEL-H (IAC, IEIIT, IFAC, IMATI, IREA, ISTI)**

Development of computational bio-electromagnetics techniques for brain invasive and non-invasive stimulation by electro-magnetic fields for neuro-disorders; bioelectric modeling of nerve fiber for novel sensory-motor prosthetics; modelling of microwave and radar applications for diagnosis, surgery and oncology; EMF characterization of human tissues in vivo, development of electro-physical models to study the interaction between single cells and pulsed electric fields in cancer therapy.

Modeling of: i) physiological and pathological processes, in terms of structural components and their interactions, to derive mathematical expression for simulation and further symbolic and numeric manipulations, with applications in pharmacological investigation and in research on kinetics and metabolism of endogenous substrates and xenobiotics; ii) immune system considering its involvement in the resolution or the exacerbation of human diseases; iii) blood flow in normal and pathological conditions and
development of algorithms for EEG/MEG processing in physiology and pathology, iv) of gene regulatory networks (GNRS) by computational frameworks, to facilitate network analysis and design.

HTECH (IEIIT, IFAC, IGI, IMEM, IREA)

Design and development of EMF-based biomedical devices for non-invasive breast cancer and brain stroke diagnosis, thermal treatments guidance and hyperthermia and ablation by microwaves; magnetic nanoparticles hyperthermia and tracking for drug delivery; invasive and non-invasive brain stimulation for neuro-disorders; electrochemotherapy by pulsed electric fields for tumor treatment.

Development of technologies for early diagnosis and assessment of hearing impairment, of gestural human computer interfaces to automatically assess the neurological status in Parkinson patients and of bioreactors aimed at in vitro testing and validation of novel drug delivery approaches.

Development of invasive optical fiber sensors to monitor biomedical quantities and optical platforms for biomarkers for sepsis and immunosuppressants in transplanted patients; plasma sources for treatment of corneal infections, disinfection, wound healing, cancer therapy killing damaged cells by, non-thermal blood coagulation and transfection of genetic material.

Activities related to Point of Care Diagnosis by developing nano-micro, organics, bio-organic and hybrids hierarchically organized materials, sensors and systems, for diagnosis and therapy; systems for acute, post-operative and chronic pain therapy by drug-delivery by nano-micro containers; detection of neuronal activity and biomarkers by OECT (Organic Electro-Chemical Transistor); tissue engineering by OECT on textile fibers, to monitor the concentration of salts in the sweat, to prevent states of dehydration and malaise; hybrid nanosystems for RX-induced photodynamic therapy.

T-PERMED (IAC, ICAR, IIT, IMATI, ISTI)

Development of tools and algorithms to integrate and process huge amounts of structured data, biomedical images, signals, text, also collected in Virtual Reality environments, by means of machine/deep learning, pattern recognition and natural language processing techniques. Specifically: i) segmentation and annotation of biomedical images and the extraction of 3D geometric descriptions, also supporting new multi-modal visualization modalities; ii) radiomics approaches for the extraction of quantitative features from biomedical images to model their inner information and create reference biobanks meant to support research activities; iii) connectomics approaches exploiting novel complexity measures for the extraction and modelling of features from signals; iv) epigenetics approaches for the identification of the chromatin structure on available human genome.

Modelling of various medical contexts as well as decisional procedures elicited from experts or learned from data to support personalized diagnosis, monitoring and prevention of pathologies, by using both knowledge technologies and artificial intelligence algorithms and tools. Contribution, by network-based analysis, to the discovery and multi-dimensional combination of effective diagnostics biomarkers and, by graph theory, machine learning and statistical inference techniques, to predict treatment response and disease progression. Novel solutions for enabling the interaction of healthcare systems with humans by using gestures and natural language.

E-HEALTH (ICAR, IIT, IMATI, STIIMA)

Launch of specific actions, under the agreement/collaboration with the Agency for Digital Italy, finalized to: i) design and validation of ICT platforms for the interoperability of health critical systems in compliance with the current regulations, especially on Electronic Health Record (EHR); ii) standardization of the structure of clinical documents and the use of terminological systems for coding the clinical content appropriately. As far as the development of the EHR national system is concerned: i) modelling of health business processes; ii) definition of access control and information integrity mechanisms (cybersecurity); iii) development of technical specifications and health informatics standards; iv) implementation of testing environments.
CNR participates to the EHR National Board, under which the EHR national interoperability framework has been defined and implemented by all the Italian Regions. Other activities: development of coding support web services, based on formal rules; integrated terminology services based on standard semantic interoperability protocols to support the stakeholders in the terminology management and use; optimization of document management and preservation processes within healthcare facilities, including the analysis on conformity to standard specifications; alignment and improvement of models to measure the quality management level of hospitals and highlight best practices; documentation and annotation of patients’ data and integration of different exams/data/information to be shared among different specialists.

3. IMPACT

**DIGHEALTH**

The AP HWB research on digital solutions for health monitoring and promotion have a strong social impact in terms of citizen empowerment through self-monitoring, personalised coaching, persuasive feedback and access to personal data. In addition, it has a strong scientific impact for the health communities, highly increasing the amount of data characterising the individual behaviour and needs, in addition to the definition of new algorithms for data mining and analytics. From a political point of view, this activity contributes to enable EU citizens to: i) lead healthy, active and independent lives while ageing; ii) improve the sustainability and efficiency of social and health care systems; iii) boost and improve the competitiveness of the markets for innovative products and services, responding to the ageing challenge at both EU and global level, thus creating new opportunities for businesses.

**S-ROB**

Robotics technology in synergy with advanced smart environments has the potential to promote well-being at home and in assisted facilities by implementing both a monitoring and coaching/motivational role. The AP HWB research activities on this topic has a potential impact in the realization of health and well-being services that could help address the demands of an ageing population and an increased pressure on centralised healthcare systems, which entails an increasing interest in multiple functions and continuous monitoring delivered at home. This is in line with the goal of the European Commission of pursuing policy initiatives relevant to the Silver Economy, e.g. on the potential for new markets and economic drivers such as independent living.

**ENVHEALTH**

The AP HWB research activities on the interaction between the human health and the quality of the environment has a strong impact at social, scientific, political and industrial level. On the social level they are providing evidence-based information to health authorities and general public about the possible health risks related to EMF exposure and a better awareness of the EMF exposure level to which the general public (and workers at the workplaces) are exposed. Moreover, AP HWB research allows to collect evidence-based information on the link between exposure to physical agents and health status of the involved population. On the scientific level, the impact of the research activities is, at first, in contributing to fill the gaps of knowledge on the effects of EMF exposure on health and to improve EMF exposure assessment techniques. Additional impacts are in providing expertise and input to health risk assessment processes, which are put in place by national and international bodies (WHO, EU-Commission, IEEE, etc.) and in providing real-time cancers/pollutants risk maps (leukemia, myeloma and lymphomas vs chemical pollutants in air and food). The main impacts on the industrial level are in the improvement of technological techniques to reduce EMF exposure and in the development of new hi-tech tools for the measurements of EMF and other physical agents. The identification of scientific evidences to support policy authorities in implementing the actions needed for risk management and risk communication processes, including the possible link between cancers and pollutants, are the main impacts of AP HWB activities on the political level.
**MODEL-H**

The increase of the knowledge on neural mechanisms and their control, the investigation on brain network dynamics for neuro-prosthetics and the in silico characterization of the EMF quantities induced in neural tissues during brain stimulation are among the main scientific impacts of AP HWB research on in silico models for health. Additional relevant studies are the investigation of the dynamics of the neural processes in normal and pathological conditions, the development and in silico test of innovative drugs (including the determination of dose/schedule therapeutics protocols) and the investigation of multiple therapeutic approaches and diagnostics for oncology.

A relevant social impact is related to the validation of new diagnostic and therapeutic techniques, devices and drugs, to reliably accelerate their use on a large scale to the benefit of the largest possible number of patients, together with the improvement of personalized medical treatments.

Industry is taking advantage by the AP HWB results mainly in the design and prototyping of innovative medical devices and in descriptive and interpretative structural models for pharmaceutical industries.

The reduction of social costs by facilitating the introduction of new devices, the discovering of links between health conditions that were once considered unconnected, the uncovering of shared disease mechanisms and of key drivers of pathogenesis, and the identification of novel therapeutic applications, avoiding drug side effects, are strongly impacting on the health services at political level.

**HTECH**

The AP HWB results on innovative tools, technologies and devices for advanced diagnosis and therapies are strongly impacting the scientific community, mainly for what concerns the design and development of new EMF-based biomedical applications, including the combination of multiple therapeutic approaches and diagnostics for oncology and the technologies for individualized drug therapy. Moreover, the contribution to the development of novel treatments of tumors and wound healing (e.g., plasma, pulsed electric fields) and the development of novel technologies to apply external stimuli and collect in vitro biological, mimicking the physiology of human organs, are of relevant interest. From the social point of view, AP HWB activities are contributing to provide the health systems with new EMF-based economically-sustainable technologies. Availability of minimally invasive devices at home for a better quality of life of patients, the decrease of the mortality in many pathologies by rapid and reliable monitoring of disease markers (e.g., by Point of Care Testing and Diagnosis) are among other strong social impacts of AP HWB research. On the industrial level, AP HWB research is contributing in providing high-tech opportunities for the biomedical industry to stay at the cutting edge of the technological research and development. Last but not least, the decrease of the costs of the health services by the reduction of the burden of diseases, thanks to the introduction of novel technologies and tools for the advantage of patients and families, are strongly impacting at political level.

**T-PERMED**

AP HWB activities have already generated a relevant impact in healthcare settings. In particular, CNR has formalized: i) agreements with regional and national health organizations and local companies of the health domain to realize ICT solutions for aiding care activities; ii) the constitution of a center for experimenting AI solutions to significantly advance research and care, especially in oncology, with big industry players and health organizations; iii) participations in regional and national scientific committees in the health domain. Moreover, future expected results can have a significant impact at scientific level. Methods, techniques and tools specifically realized for personalized medicine will be validated in the daily practice, allowing quantifiable measures for the evaluation and the interpretation of their outcome. Thus, more accurate diagnosis of pathologies of different specialties can be achieved. Moreover, links between conditions currently considered unconnected can be discovered, by uncovering shared disease mechanisms and key drivers of the pathogenesis, predicting individual disease outcomes, and identifying novel therapeutic
applications also avoiding drug side effects. In addition, consciousness indices can be improved and validated to better classify neuropathological conditions of unhealthy patients by comparing diseased and healthy connectomes. The relevance of the expected results can be also extended to industry, since the proposed solutions could be engineered and integrated in decision support systems. Finally, the clinical validation can also boost pharma companies.

E-HEALTH

AP HWB activities have already produced a significant impact given the strong cooperation with the competent institutions (Agency for Digital Italy, Ministry of Health, Ministry of Economy and Finance), in order to ensure national (among the 21 regional EHR systems) and, potentially, European technical and legal interoperability according to the constraints imposed by the current laws. Moreover, the specifications produced as part of the Italian implementing decrees represent the technical reference for the homogenous implementation of such systems by the majority of the e-health industrial vendors. 

In addition, granting interoperability of clinical data has also a strong impact since the comprehensive understanding of health processes and data flows is crucial to plan and manage policies and services, also enabling the meaningful reuse of information for a plethora of secondary scientific, social and political purposes. It can also ensure EU cross-border interoperability to enable health data exchange and understanding, despite of their native format and language in order to provide EU citizens efficient care, even if they are not in their own country.

4. EMERGING RESEARCH CHALLENGES

Integrated solutions for self-monitoring, health promotion, disease prevention, and management of chronic conditions/multi-morbidities. Personalised and exhaustive coaching based on real world data.

Safe, smart and efficient robotics based on AI. Advanced human-machine interactions and complex embodied systems.

EMF assessment and interaction of 5G technologies. Data integration, analysis and visualization on a geographical scale for health-environment monitoring.


Heterogeneous data exploitation for tailored disease diagnosis/treatment. Immersive and tailored rehabilitation, surgery and prosthesis.

Deep analytics for document/knowledge management, optimization of EHR workflows, meaningful organization of clinical knowledge.

5. CONCLUSIONS

AP HWB gathers the scientific activities of CNR DIITET in the area of engineering and ICT for medicine and health. Currently it involves 142 structured personnel units (researchers, technologists and technicians) and 38 assistant researchers distributed over 12 CNR DIITET Institutes.

AP HWB activities are fully in line with the main European and international indications regarding the development of this specific sector. Specifically, the pillars on which AP HWB’s research and development activities are based, are in line with the current H2020 program and the preliminary information about Horizon Europe research challenges. In addition, they follow also other international programs, like the NSF program on Smart and Connected Health (SCH), aimed at accelerating the development and integration of
innovative computer and information science and engineering approaches to support the transformation of medicine and health.

These activities move, first of all, along the two primary research lines generally identified as the real challenges for medicine and health in the near future: personalized medicine and digital transformation of health and care process.

On a practical ground, AP HWB implements these lines with a system based on the 7 scientific research pillars discussed above.

These activities are made possible by the involvement of extremely different skills: bioengineering, applied electronics, applied electromagnetism and microwaves, computational biology, bio-modelling and control systems, system and communication engineering, information theory, pervasive and mobile computing, artificial intelligence and data analytics, robotics and virtual/augmented reality.

Furthermore, HWB activities are strictly linked but not overlapped with activities performed by other CNR DIITET APs, such as AP Biotechnologies, Cyber Security, Nanotechnologies, Robotics and Automation, Smart Cities, Social Security.

AP HWB, with its research groups, is an international reference point in the various specific sectors, as demonstrated by the large number of multi-centre European and international projects in which AP researchers are involved, and the wide research and industrial network they are maintaining in this field, also through the participation in national and international working groups.
AP9 BIOTECHNOLOGY

EXECUTIVE SUMMARY

The present document summaries the scientific activities of about eighty scientists and eleven CNR institutes. These activities can be traced down up to the birth of biotechnology and bioinformatics activities in Italy, which were actually born within CNR.

The growth of the biotechnology research and related industry in the recent years has been unprecedented; advancements in molecular modeling, disease characterization, drug discovery, personalized healthcare and agriculture fundamentally impact economic and social issues in the European scenario. When bioinformatics approaches and technological innovation meet the demands of biotechnology (e.g. environmental biotech, drug design and discovery, genomics, regenerative medicine), relevant breakthrough research is carried out, as recognized by the significant number of project and publications of CNR-DIITET personnel. This growing importance is not only because bioinformatics handles large volumes of data but also in the usefulness of bioinformatics tools to predict, analyze and help interpretation in clinical and preclinical findings.

One of the greatest challenges facing the CNR DIITET biotechnology community is to be able to make use of the vast and dynamic influx of omics data. The synchronized development of bioinformatics concepts and related computational tools for prediction and modelling is a prerequisite to enable the exploitation of this wealth of biological data as a source of new biotechnological applications. The rapid technological progress of DNA sequencing has greatly facilitated the fast mapping of microbial genomes. This, however, necessitates matching bioinformatics platforms for subsequent analysis.

This document presents the current activities of AP Biotechnology, divided into 6 pillars fully in line with the European priorities:

- Analysis, management and integration of biological big data
- Development of network-based approach towards precision medicine
- Biophotonics
- Bioprocess and Tissue engineering
- Mathematical and software tools for bioengineering and biology
- Bio-sensors and Bio-inspired systems

After a short description of the state of the art of each pillar, the current activities are described, together with their impact and the identification of the specific challenges of the next future. The description of the effort in terms of person/months, the available infrastructures and facilities are described in the annex.

1. STATE OF THE ART OF THE RELEVANT SCIENTIFIC AREA

Biotechnologies provide an ever changing and evolving scenario, where research has obtained outstanding scientific and technological results, by developing and integrating multidisciplinary competences. Such progresses have economic impacts in many different fields, such as welfare, healthcare, agriculture and industry, and as a key component in social challenges addressed by H2020 program. The research themes require competences both in base sciences like Chemistry, Physics, Mathematics, Engineering, Computer Science, Bioinformatics and Systems Biology and in more specialized ones like biotechnological, medical, material science and life sciences. Results from this area are strictly connected with those in Healthcare and Wellbeing, Nanotechnologies, Applied Mathematics, ICT Systems and Devices and Low Carbon Technologies, although the characterizing parts are peculiar to the present area.

Scientific and technological research in this field is fueled by a constant progress in technologies. The potential of such technologies requires tremendous efforts to be fully exploited.

The convergence of new measurement and visualization technologies, and new computational and mathematical tools, bioinformatics approached and systems approaches to disease models can be expected
to allow to overpass the current medicine approach, where we wait until the patient is sick before responding, with a personalized, predictive, preventive, and participatory (P4) medicine that will be cost effective and increasingly focused on wellness.

In more detail, the aim of this area is to develop novel methodologies, algorithms, software tools, hardware devices, as well as processes and technologies for clinical, medical and biotechnological applications. This aim can be reached only merging competences already available in the Institutes with those belonging to national and international collaborators. Examples can be found in different biotechnology fields: new bioinformatics approaches have been developed for gaining more insights into fundamental biological processes and functions; realization of electronic devices mimicking essential properties of biological synapses; data analysis methodologies and bioelectronic and biomechanical technologies have been carried out for advanced therapies, targeted drug delivery and sensing devices; biophotonics, embracing all light-based technologies applied to the life sciences and medicine, provides a better and earlier diagnostics, novel biomarkers, multifactorial and multigenetic diseases and comorbidity discoveries and advanced therapies; dynamic tissue engineered systems have been designed and realized to provide more realistic and controllable environments to better simulate the real human healthy/pathological conditions in vitro, thus acting as reliable platforms for generating in vitro predictive results.

The same happens in omics data production: a number of high-throughput sequencing techniques (e.g. 3C, 4C, Hi-C) have recently been developed to count the internal interactions of the DNA chain in cell populations. Since the spatial structure of the chromatin has been recognized as an important factor in gene expression and epigenetics, many 3D reconstruction algorithms are being developed, e.g., to correlate the known properties of genes with their spatial positions and relationships. One of the major challenges is to integrate the huge and dynamic avalanche of biological big "omics" data, with imaging data. The development of innovative bioinformatics approaches in the spirit of reproducible research according to the FAIR (findable, accessible, interoperable and reusable) principles, taking advantage of high performance computers, becomes a prerequisite to completely fill the gap between available clinical/biological data and our ability to structure these data in information to gain novel knowledge on relevant scientific and technological problems. Among the most challenging objectives we are going to fulfill, there are the analysis of single cell sequencing, the planning of artificial genomes for biotechnological applications, sustainable biomolecular pathways, the simulation of biological processes and functions, and the subsequent realization of artificial biological systems.

Finally, the development of novel methodologies, tools and industrial biotechnological processes based on advances technologies, such as those involved in bio-catalysis, will give rise to a class of novel products that cannot be obtained through presently available industrial technologies. Among these, the development of microbial and enzymatic processes in the framework of the biorefinery of renewable feedstock (e.g. lignocellulosic biomass residues) is a cross-cutting topic connected with low-carbon technologies and nanotechnologies. Moreover, molecular transport is the basis of biochemical cell processes (e.g., transcriptomics). Single particle tracking techniques revealed that diffusion of macromolecules is highly heterogeneous, thus posing new challenges to the understanding of the underlying mechanisms.

Nevertheless, imaging and sensing are among the main areas, where biophotonics can provide unique solutions and play an essential role. For example, big efforts of the scientific community are related to the development of sensing platform/device capable to monitor and detect bioanalytes and chemoanalytes at very low limit of detection, down to single molecule detection. On the other hand, a great effort is devoted to the development of new light-based approach, in order to induce selective and localized effects in biological tissues or biological materials. These approaches are useful in the design of personalized and precision medicine, surgery and diagnostics.

In such ever-changing scenario, we can identify several relevant scientific and technological areas, for which we are going to describe, in the next sections, contribution and impact.
2. CONTRIBUTION TO THE RELEVANT SCIENTIFIC AREA

Analysis, management and integration of biological big data (IAC, IASI, ICAR, ISSIA, IIT, ISTI)

CNR focused on the development of new statistical and machine learning approaches needed to analyze, integrate, visualize and manage biological big and high dimensional data, recognize patterns and models of behavior, as well as search innovative solutions to discover new clinical knowledge starting from biomedical and next generation sequencing data. Our tools are conceived to support reproducible computational research and promote FAIR principles of Data Science. With respect to sequence analysis, we focused on the analysis of structural variations, absent biological sequences or nullomers, and their application in immunology, cancer development, and rare disease diagnosis.

CNR also contribute to the development of novel methods for the integration of omics and clinical data with the aim of revealing and predicting the cellular mechanisms and their disruption under pathological conditions, and for identifying genetic markers underlying the onset and progression of complex and multifactorial diseases, such as cancer. Recent activities are represented by the analysis of single cell sequencing data with the aim of better understanding diseases and stem cell differentiation.

Development of network-based approach towards precision medicine (IASI, ICAR, ISSIA, IAC, ISTI)

Novel methods for validating network communities and to study the robustness of gene–regulatory time varying networks have been developed. Additionally, we also developed advanced approaches for network-based survival regression able to identifying few potential biomarkers and discriminate patients in high-and low-risk groups. Network based approaches can also be applied to precision medicine to tailor the medical treatment to the individual characteristics of each patient based on genetic, environmental, and lifestyle factors: individuals have to be classified into subpopulations that differ in their susceptibility to a particular disease, in the biology or prognosis of those diseases they may develop, or in their response to a specific treatment. The emerging tools of network medicine offer a platform to explore systematically not only the molecular complexity of a particular disease, leading to the identification of disease modules and pathways, but also the molecular relationships among apparently distinct (patho)phenotypes. This has led to the identification of new potential therapeutic targets for the treatment of different types of cancer. Furthermore, it is increasingly being recognized that quantitative description of the mechanisms connecting and regulating the various bioprocesses that sustain growth and proliferation of eukaryotic cells requires multi-scale dynamic modeling like the “whole cell” mathematical models. CNR developed a modular, coarse-grain “whole cell” model that accounts most important cellular activities, such as metabolism, growth and cycle.

Biological processes in the cell as information transfer processes, by using Shannon’s Information Theory have been also modeled. The aim is understanding how these processes are altered in cancer, since gene work in an orchestra rather than working alone. This has necessitated the development of gene interaction networks. Estimation of these networks is based on Bayesian networks and other graphical model selection methods. We also address the problem of modelling time varying gene-interaction networks using Monte Carlo for fitting a vector linear regression with time varying coefficients, and Markov chain networks to study healthy and cancer cells and understand the difference in dynamics.

Biophotonics (IFAC)

CNR is highly involved in the development of optical resonant structures/platform for the detection and monitoring of bioanalytes for both clinical and environmental applications; moreover, CNR is involved in the implementation of advanced microscopy techniques including second harmonic generation (SHG), atomic force (AFM) and Raman microscopy for diagnostics and spectroscopy of tissues and biological fluids, microscopy and photoacoustic tomography for the early detection of tumor lesions. Preclinical and clinical methods, technologies and procedures for therapeutic and surgical use, based on the use of lasers, LEDs,
biopolymers and laser-activating contrast agents for the following applications have been also developed. CNR launched several actions on laser-induced repair of biological tissues (ophthalmology, microvascular, neuro) and haemostasis induced by high-power blue-LED (vascular dermatology).

**Bioprocess and Tissue engineering (IEIIT, IRC)**

Concerning advanced biofuels production through the lignocellulosic sugar platform, main open issues related to the current technical barriers to the process commercialization have been addressed. Novel integrated pretreatment and hydrolysis processes for saccharification of biomass from agro-food wastes, kinetic characterization and optimization of enzymatic hydrolysis of biomasses, and catalytic conversion of ethanol into butanol have been reported. CO₂ capture through enzymatic reactive absorption processes has been developed in terms of biocatalyst design through the characterization of free enzyme catalysis at industrially relevant conditions, the immobilization of enzymes by covalent attachment and by carrier free techniques, the modeling of absorption units operating with the developed biocatalysts.

Bioreactor technology together with in silico modeling to replicate the physiological complexities of portions of human organs. In particular, fluidic bioreactors are designed and realized with advanced technologies (3D printing) for different healthy/pathological applications, for (i) mimicking the fluidic and mechanical stimuli of articular cartilage and validating novel implants for orthopedic application, or for (ii) reproducing in vitro the fluidic stimuli of the micro-circulatory system and testing the new drugs stability within the circulatory systems.

**Mathematical and software tools for bioengineering and biology (ISSIA, ISTI, IMATI, ICAR)**

CNR studies cancer mutations from a statistical point of view. The cancer mutations, unlike evolutionary mutations, do not have a Poisson dynamics but a Pareto-law dynamics. We are currently working on developing parametric models for cancer mutations similar to the Kimura model for evolutionary mutations.

Further work is focused on the production of personalized medical products and devices through new design approaches and technologies, in an environment closely integrated with the hospital, which guarantees the direct contact between patients, medical personnel and devices manufacturers. This has the potential to drastically improve the quality of life of people, the performance of health care services and the competitiveness of medical products manufacturers. In particular, advanced mathematical and modelling technologies will be applied to build the anatomical model of patient through the combination and analysis of bio-images; the model is sent to a “hospital factory”, which can be located inside the hospital or closely integrated with it by the adoption of real-time connection tools; the hospital factory is able to produce the personalized product in a very short time, thanks to the combination of a set of innovative technologies (such as additive manufacturing, micro-EDM, micro-extrusion) and processes to manufacture personalized products; the personalized product is implanted to the patient with the guarantee of optimal size, fitting and comfort, and with minimum time and complexity of surgery.

Besides products, the hospital factory will produce also personalized anatomical models (e.g. cardiovascular models) that can help surgeons to study patients’ pathologies treatment in advance, in order to simulate different surgery strategies.

**Bio-sensors and Bio-inspired systems (IMEM)**

Organic memristive devices, the element that was specially developed for mimicking synapse properties, were successfully used for the realization of artificial neural networks, systems with long-term potentiation and depression, as well as short-term potentiation and depression (similar to those in nervous system), and even for making simulations of neurodegenerative disease pathology. It has been shown that it is possible to use them in electronic circuits capable of learning according the Hebbian rule. It was also shown the possibility to provide an artificial synaptic connection between two nervous cells from the rat brain cortex.
The continuation of these works has resulted in the preparation of proposals, as that submitted to the H2020 FET-Open program.

Electrochemical and field effect devices based on organic conductors and graphene layers are currently developed, together with other electronic platforms, for different applications, such as biosensing, monitoring of biological system activities, neuromorphic applications, etc. All the devices are prepared through different technological processes, such as electrospinning, Langmuir-Schaefer procedure and lithographic techniques, and are endowed with innovative features, such as Additive Manufacturing. Chemistry of functional materials and surfaces, together with specific device architectures, are currently aimed at enhancing devices performance and at conferring multifunctional aspects in terms of device operation.

In the field of smart containers for targeted delivery and induced release of drugs, several pioneering approaches for fine targeting and disease-induced release have been developed. Further development of these studies is focused on the realization of smart implants, containing diagnostic tools, containers with appropriate drugs, release triggering tools, and antenna and electronics for the communications with patients and physicians.

3. IMPACT

Analysis, management and integration of biological big data

Today it is necessary to develop new techniques of analysis on big data to cope with the increasing volume of genomic and proteomic data. Efforts to build biological data base management systems that allow efficient access to non-expert users will enlarge the number of data science studies on the huge amount of data collected in the bioscience domain, so providing a continuous increase of the knowledge about biochemical mechanisms and processes that are the base of the life and dead of cells. The development of faster machine learning algorithms together with the analysis and integration of different layers of information and big data sets will allow to deeply investigate the origin of cellular mechanisms and their disruption under pathological conditions, and, as consequence, to identify novel therapeutic targets and strategies.

Developing innovative solutions dedicated to the data analysis and predictive models allows the researchers to identify the interactions among essential components such as miRNA, mRNA and proteins that are responsible for the development of cancer diseases or chronic diseases with a high economic impact.

Moreover, the study and development of tools for information integration may enhance the analysis of biologists and physicians, to shed light on mechanisms triggering disease.

Computational tools that support reproducible computational research and FAIR (findable, accessible, interoperable, reproducible) principles of data sharing and management will lead to more transparent results.

Development of network-based approach towards precision medicine

The emerging approach of the precision medicine has enabled a new era of health care delivery and treatment. Understanding of the underlying mechanisms of high-impact diseases is allowing scientists to develop new drugs, targeted therapies, and preventive strategies. SWIM represents a solution of excellence addressing these issues that can improve the knowledge of the cellular events crucial for carcinogenesis and may unveil many potential prognostic and novel therapeutic targets. Using SWIM could provide important clues that will stimulate research activities into the causes of high-impact diseases, including but not limited to human cancer, thus supporting the planning of healthcare services such as clinical trials and disease prevention.
Moreover, the development of network-based approaches can help clinicians to provide more precise prognoses and to facilitate the subsequent clinical management of patients at risk of disease.

Predictive “whole cell” computational models are supposed to be exploited in personalized medicine, whenever a specific drug administration therapy is required to be tested on single virtual cells or populations of virtual cells, possibly adapting the individualized therapy to an environment subject to changes and uncertainties.

**Biophotonics**

The development of devices capable to achieve single molecule detection, or in any case very low limit of detection is a challenge which is pursued in the scientific world at international level; besides the intrinsic scientific importance to identify and monitor single molecules which can open new knowledge in the comprehension of the their physics and chemistry, the measurement of analytes at very low concentrations can play a fundamental role in medicine in the detection of the onset of pathologies at a very early stage: this can have an huge effect for the patients thanks to the administration of the correct therapy well in advance, as well as it can affect the social systems with a noticeable decrease in the healthcare expenses.

The use of light- based devices can be used in a tailor-made surgical application: this technology is useful in the realization of precise and customized surgical cuts and suturing patterns; or it can be used to design cardiovascular stents perfectly matching the patient’s anatomy. All these approaches are at the basis of the precision and personalized medicine.

**Bioprocess and Tissue engineering**

Novel bioprocesses based on microbial and enzymatic biocatalysts play a crucial role in the impact of industrial biotechnologies on circular economy. The contribution by biochemical engineering science is mainly related with the development of novel biocatalysts and their characterization aimed at their use through rational design of bioreactor units towards the integration of unit operations (e.g. bio-separation processes). The integration of fermentation and recovery units for the production of bio-butanol through the ABE fermentation process is an example of how the novel industrial bioprocesses can act to improve productivity in biorefinery plants. Similarly, the investigation of cellulose hydrolysis catalyzed by cellulase cocktails aimed at the design and set up of novel bioreactor configuration for efficient recovery of fermentable sugars from lignocellulosic feedstock contributes to the development of sustainable processes for the production of second generation biofuels.

The potential impact of tissue engineering (TE) based technologies is that they can act as more predictable R&D platforms, by providing more physiologically relevant conditions than 2D culture and/or animal models. Moreover, these TE technologies could be adopted as in vitro screening platforms. Enabling the availability and effectiveness of personalized and predictive screening tools for therapies that will prevent or limit spread of diseases is one of the biggest unmet clinical challenges at the moment, both for the scientific and the industrial pharmaceutical community. Providing suitable options to the high cost, inefficient and ethically complex use of animal models in pre-clinical research and development phases, with better chances of success in clinical trials is another challenge for the scientific and industrial research community, and the society.

**Mathematical and software tools for bioengineering and biology**

The demand of more intensive and advanced healthcare services is clearly in contrast with the general pressure to reduce the cost of healthcare systems in the European countries, due to national financial sustainability reasons. Consequently, new innovative models are required to solve this paradox in order to continue guaranteeing the growth of social and health conditions of citizens. These models should break the usual boundaries of the existing healthcare systems, not only in terms of medical services and healthcare
excellence, but also in the field of technology and industry, which is a fundamental enabler of the value provided to customers in healthcare services.

Our activity has the following scientific and technological impacts: define new statistical methods and approaches to elaborate an accurate anatomical model from bio-images in order to design personalized products; define improvements to the existing technologies for personalized products, to lower production costs, thus allowing the wide diffusion of personalized medical products; propose innovative process combinations and manufacturing approaches; demonstrate the new technological approaches in real products and medical scenarios.

**Bio-sensors and Bio-inspired systems**

The progress of systems for bio-mimicking information processing requires the use of synapse-like electronic elements what will allow to combine memory and processor in a single system. Such system will allow learning at the hardware level and parallel information treatment. Developed devices and networks will mimic some functions of the nervous system and brain, what will make possible experimentations that are impossible or forbidden to perform on animals and brains. Finally, such devices are expected to be interfaced with nervous system for recovering damaged parts and to control prosthesis.

As all pharmaceutical preparation have side effects, ideal container must provide their delivery to the diseased areas of the body or to the zones of risk, and the active drug must be released when the disease occurs. In this respect, containers based on nanoengineered polymeric capsules are very challenging. The whole internal part of these object can be filled with active drug, while their shell architecture (incorporation of magnetic nanoparticles and receptors for targeted delivery and special compounds for induced release) guarantees that the drug will be delivered in a proper area and the release will occur only in the case of disease.

The short-term perspectives are focused on the accumulation of a robust and diversified technological experience in the fabrication of different device structures, through the combination of several advanced and powerful technological tools, and on the implementation of novel characterization protocols.

In the medium-to-long term, organic biosensors and devices will be customized with different structural properties and features to optimize the response with respect to specific application scenarios and to widen the portfolio of potential application fields; moreover, OECTs will be miniaturized and transferred onto biocompatible substrates for in-vivo biomedical applications.

### 4. EMERGING RESEARCH CHALLENGES

1) Development of statistical algorithms and computational tools for connecting resources, integrating imaging, sequencing omics data for human health and ecology.

2) Novel algorithms and precision molecular tools to explore the diseases molecular complexity. Efficient, scalable algorithms for high-throughput omic-analysis, visualization methods of reconstructed structures.

3) Single-molecule detection based on optical resonating structures; realization of personalized and precise surgery, tailor made on patient’s organ morphology.

4) Novel pathways for integrating thermo- / bio-chemical conversion processes. CO₂ capture and use through microbial and enzymatic processes. 3D healthy/pathological models for the study of micro-environmentally driven cellular mechanisms.

5) New models to guarantee the growth of social and health conditions of citizens.

6) Realization of implantable devices controlling drug release, and artificial analogues of nervous system damaged parts for implantation.
5. CONCLUSIONS

Biotechnology provides a constantly evolving scenario, where research has achieved significant scientific and technological progress using and integrating multidisciplinary skills. These advances have economic repercussions in many sectors, such as health, agriculture and industry, and in support of the various social challenges of the European H2020 program. The research topics addressed in this project activity require skills in both technology, medical, and life sciences. As described in the present document, the activities within the DIITET provide results with close ties with other design areas such as Healthcare and Well-being, Nanotechnology and Applied Mathematics and Low Carbon Technologies. In particular, the aims of this design activity are focused on developing new methodologies, algorithms and software tools for synthetic biology, new bioinformatics approaches in clinical, medical and biotechnological fields, industrial biotechnological processes, data analysis methodology and advanced therapy technologies, biophotonics. Scientific results are achieved by putting the existing skills in the CNR-DIITET Institutes involved with those of the national and international realities with which they work together.

The results attest a gradient ascending direction towards major achievements in terms of scientific contribution, the ability to collaborate in national and international research projects, and young scientists training.
AP10 ADVANCED MATERIALS AND NANOTECHNOLOGIES

EXECUTIVE SUMMARY

AP10 includes interdisciplinary skills for the synthesis, characterization, modelling and development of innovative materials and nanotechnologies for industrial processes, environmental, energy and bio-medical applications. The activity addresses both the H2020 (EU) and PNR (IT) programs in particular the Leadership Action in Enabling Industrial Technologies, Future and Emerging Technologies, Nanotechnologies, Advanced Materials, Biotechnology and Advanced Manufacturing and Processing.

The materials and nanotechnologies developed in AP10 have a strong social and economic impact in particular for the industrial leadership and societal challenges.

CNR institutes have developed and established high-level skills aimed at the nanoscale level production of new or advanced inorganic, polymeric and hybrid materials. The main objectives are addressed to the development of materials and nanotechnologies for electronics and magnetism, optoelectronic devices, plasmonic systems, photonics, nanofluids, for (bio-)sensors and for energy. Electronics materials include nanostructures for high power electronics, 2D materials like graphene or dichalcogenides, Qdots, organics, semiconductor and functionalized oxide nanostructures. In the energy sector, materials for catalytic processes, e.g. CO₂ recycling, electrochemical storage, nanofluids, electrolysis, hydrogen and CO₂ storage and high efficiency fuel cells fed with hydrogen and alternative fuels, adsorption heat pumps, photocatalysis and photovoltaics are currently developed.

Nanotechnology offers radical alternatives for numerous medical problems, e.g. in the contexts of oncology and biosensors. The materials range from multifunctional optical and/or magnetic contrast agents, capable to systemically recognize malignant lesions and enable their diagnostic imaging and treatment, to tissue engineering developing of scaffolds for bone and articular tissue regeneration, to bio-mimetic hybrids for biocompatible electronic systems, to optical devices to assess the effect of new drugs on individual cells and to hybrid solutions for intracellular delivery of nanoprobes.

All these activities are supported by increasingly important numerical modelling and simulation studies for the prediction and processing of data and processes.

The AP involves multi- and interdisciplinary aspects since the development of advanced materials and nanotechnologies for a wide range of applications is strongly based on the use of highly complementary and converging skills. This is confirmed by the quality and the number of research projects, both at European (20) and National (21) level and the relevant number of person months per year (743) involved on this theme.

1. STATE OF THE ART OF THE RELEVANT SCIENTIFIC AREA

Advanced materials introduce new functionalities, improve properties, and, at the same time, add value to existing products and processes, in a sustainable approach. Nanotechnologies can be used to create nanomaterials having new properties due to the nano-scale, or can be used to develop nano-devices.

1.1 Advanced materials for industrial processes.

Electronic industry requires materials for high power electronics. SiC and Ga₂O₃ are considered very promising for these applications. CdZnTe is considered the best material for preparing room temperature operating spectroscopic x- and gamma ray detectors. Semiconductor and metal oxide nanostructures (μtubes, nanowires, nanosheet) as well as graphene and C-base nanostructures (1D sheets, nanoribbons) were proposed for novel sensors, energy storage, optoelectronics, nanoelectronics, nanocatalysis. 2D transition metal dichalcogenides (MoS₂) are alternatives to the gapless graphene. MBE-grown semiconductor QDs are 0-dymensional systems with quantum-mechanical properties that can be managed, tailored and implemented into device-like structures. Thin films of small molecules are the basis for organic
electronics. **Surface functionalization** can be the key for enhancing material properties such as inorganic nanowires with organics for sensing and biomedicine or graphene and polymers with biomolecules for high sensitivity/selectivity biosensing.

**Multifunctional magnetic materials**, with functional properties (e.g. thermal, mechanical, electrical, optical) tuneable by the combined application of external stimuli are gaining an increasing interest. Magnetic thin films and spatially confined nanostructures show emerging properties that can be suitably applied in non-volatile memories, magnetic MEMS, and sensors. The synthesis and study of new magneto-electric **multiferroics** (MF) materials is a hot topic.

**Nanofluids** are fluids or solids added with nanoparticles of various metals with the following potentialities to increase the heat transfer coefficient of the base fluid, thus enhancing its the thermal conductivity without increasing its viscosity, to improve the tribological properties of lubricants to enhance the efficiency of machines or to increase the thermal conductivity of phase change materials (PCM) to enhance heat conduction in heat storage devices and in building materials.

**Structured catalysts** are widely used in large and small-scale applications due to the high specific geometric area, the low pressure drop and the enhanced mass transport. **Reactors foams** with high pore density are generally preferred to honeycombs thanks to their outstanding gas-to-solid heat- and mass-transfer properties and high specific geometric surface areas.

**Nanomaterials** are largely exploited for industrial devices and processes, such as the deposition of coatings by Physical Vapour Deposition.

Sustainability in **machining process** is facing the difficulty to cut materials for aeronautic and aerospace applications. An open issue is the development of hybrid preparation methods (additive/subtractive) combining sustainability and high production rate.

**Rare-earth-doped glasses** and **nano-glass-ceramics** are studied for optical amplification, lighting and photovoltaics.

**Modelling** of complex systems has become an essential tool, in particular for: i) dynamic processes and complex flows ii) suspensions, emulsions, gels, foams, etc.; these materials are described as viscoelastic liquids with a rheological model provided in the form of constitutive equations. Specific challenges include modelling and simulation of micro and nanoflows and manufacturing processes (composite and laminated materials, yarns).

### 1.2 Enhanced materials and nanotechnologies for energy and environment

**Nanosized and nanostructured** materials based on metal alloys, semiconductors, oxides, and carbonaceous systems have shown excellent potentialities for energy conversion and storage systems. Most of the relevant processes make use of **critical raw materials** (CRMs) in large amounts, thus determining high capital costs. An improvement of efficiency and durability in the next generation energy processes requires developing new nanostructures, such as core-shell systems and mesoporous morphologies, while providing a better comprehension of surface properties. Development of **electrorheological materials** to enhance the performance of military vehicles and medical devices used for rehabilitation will represent an important area of application in the next future.

Out-of-equilibrium deposition techniques allow the growth of **thin films for photovoltaic** conversion with desired stoichiometry.

The emerging class of **magnetocaloric materials** is gaining an increasing attention for its possible exploitation in power generation and magnetic refrigeration, an eco-friendly alternative to current cooling technology. **Magnetic materials** play a crucial role in low-carbon technologies. A significantly growing interest is devoted to their multiscale optimisation and to the design of new materials based on non-critical and easy-recyclable elements.
Metal oxide nanomaterials are used also for **energy harvesting**. The design of flexible, efficient, versatile piezoelectric devices is a challenging issue.

**Organometal halide perovskites** are promising materials for energy production.

**Photocatalytic nanomaterials** are exploited for air and water depollution, both as remediation and prevention approaches. Main obstacles to a widespread adoption of photocatalytic depollution technologies are the low activity and the requirement for UV radiation.

### 1.3 Advanced materials and nanotechnologies for bio-medical use

The clinical practice for **bone repair** is still based on the use of transplants and/or autografts. Treatment options for articular cartilage defects are just palliative. The level of biomaterials development is still inadequate in terms of long-term effectiveness and final patient outcome. Engineering functional tissues requires effective organization of cells into grafts with morphological and physiological features resembling those in vivo. The development of nano-functionalized materials mimicking the nano-features of physiological tissues could be an effective strategy. A challenge is the development of a material having mechanical properties similar to bone and good osseointegration.

Magnetic and multifunctional properties of **magnetic nanostructures** allow new-concept diagnostic and therapeutic approaches.

**Plasma processes** are useful for sterilization or decontamination of nanomaterials for bio-medical applications.

**Functionalization of oxides surfaces and nanomaterials** paves the way to tune the system electronic properties, to achieve biocompatibility or sensitivity to specific analytes, and offers newly designed alternatives in the oncological and tissue regeneration context.

The thriving field of **biophotonics** is pushing for new materials, such as plasmonic substrates for surface enhanced Raman scattering (SERS)-based biosensing of markers and pathological conditions in trace amounts, nanoparticles for systemic delivery of theranostic agents and nanotechnology-enabled photonic devices as intracellular probes, scaffolds for controlled drug release, photothermal or photoacoustic transducers, etc.

Drug release in biomedical devices can be **modelled**. In particular, the dynamics of a drug, diffusing from a polymeric matrix towards a biological tissue, affect its absorption properties, in order to optimize its therapeutic efficacy. Applications are for drug-eluting stents, medicated patches or orthopaedic implants.

### 2. CONTRIBUTION TO THE RELEVANT SCIENTIFIC AREA

Activities carried out in AP10 are characterised by a transversal nature since they involve Physics, Chemistry, Mathematics, Engineering, Biology and Medicine. For sake of simplicity, the developed materials and nanotechnologies are grouped into specific categories according to their relevant properties and fields of application.

#### 2.1 Advanced materials for industrial processes

IMEM is focused on materials development for electronics and magnetism. **Magnetic materials** are studied for applications in eco-sustainable technologies. The activity is addressing the design, synthesis and multiscale magnetic, structural and functional characterization of **rare-earth-free materials** and **nanocomposites** for permanent magnets, **nanostructured alloys** with giant magnetocaloric and magnetomechanical properties, new **metastable multiferroics**, Si-integrated magnetic and magneto-optical materials for memories and sensors.

Significant efforts are carried out at IMEM on materials for electronics with the aim to advance in sensing technologies, semiconductor devices, light emission, telecommunications etc. The new nanostructures
regard low-D materials, e.g. quantum dots (QDs), and 2D-matериалs such as graphene deposited on metal or SiC exhibiting enhanced reactivity to CO and H₂ gases. Thin FeOₓ films on metals are studied as catalyst for N₂O decomposition. 2D MoS₂ is prepared by chemical vapor deposition and ion jet deposition to control the electronic properties by defects creation and organic functionalization. Advanced deposition methodologies such as molecular beam epitaxy are used to form In(Ga)As-based QDs for telecom wavelengths emission.

**Graphene monolayers** are grown at IMEM by supersonic molecular beam deposition (SuMBD) of C60 on Cu and by dehydrogenation of hydrocarbons. The reactivity of defected/N-doped graphene towards CO is studied for gas sensing purposes. SuMBD is also used for functionalization of SiO₂ or TiO₂ surfaces by organic molecules for synthesis of 3C-SiC nanoislands on Si at room temperature rather than 1000°C as of traditional approaches and to deposit thin films with higher structural/charge transport properties for advanced organic field-effect transistors (FETs) and light-emitting FETs.

A field of increasing interest is the growth and characterization of electronic materials, from bulk crystals to nanostructures. This involves development at IMEM of CdZnTe crystals for x-ray detectors, semiconductor and oxide thin films by PED, CVD for photovoltaics, epitaxial growth of SiC and Ga₂O₃ films for high power electronics and UV photodetectors, MBE growth and fabrication of InGaAs/GaAs strain-induced rolled-up microtubes, **metal oxide nanostructures** for gas sensing, memristors, optoelectronics, transducers, catalysis, energy harvesting and storage. The fabrication of nanostructured devices is carried out by optical photolithography and FIB.

ITC is strongly involved in the characterisation of nanofluids of different nature with the aim to optimise their formulation in terms of nanoparticles dispersion, size and material selection, thermophysical and tribological properties with reference to heating, ventilation and air conditioning and for building applications.

Fluids are also actively studied at IAC by using **modelling and simulation of dynamic processes and complex flows** (suspensions, emulsions, gels, foams). Materials are described as viscoelastic liquids with a rheological model in the form of constitutive equations. Modelling and simulation at IAC include **micro and nanoflows** as well as manufacturing processes for composite and laminated materials, and yarns.

Of particular interest is the activity developed at IMAMOTER on metal oxide nanomaterials for applications in gas sensing with environmental implications. The developed nanotechnologies for chemical and biological sensors allow real-time monitoring for the environment, process and quality control, and for degradation processes. IMAMOTER also boasts excellent expertise in improving sustainable methods for machining Ti alloys and Inconel materials for aeronautic and aerospace applications.

IFP has been engaged in intensive research on plasma processes that can be used into future application areas. The study of plasma treatment of materials creates the prerequisites for innovative new manufacturing processes.

### 2.2 Enhanced materials and nanotechnologies for energy and environment

IRC is developing advanced materials for green chemistry processes, such as highly porous foams characterized by hierarchical porosity, optimized pore structure and high strength. Significant efforts are addressed to the implementation of nanomaterials such as graphene, hybrids/composites of metal organic frameworks and graphene related materials, superhydrophobic and hydrophilic coatings prepared by cost-effective solvothermal or flame synthesis one-pot methods. Innovative approaches are aimed to re-use waste materials (biomasses) in order to produce **added-value nanomaterials**.

In the energy sector, IRC is addressing the development of advanced materials for sustainable processes in particular graphene materials, supported systems and metal nanostructures used in heterogeneous catalysis.

ITAE is instead essentially focused on the development of advanced materials for hydrogen technologies, electrochemical energy storage (batteries and supercapacitors), fuel cells fed with hydrogen, alternative fuels and biofuels. Efforts are addressed at ITAE to develop innovative materials for the capture and conversion of CO₂, for adsorption heat pumps and next-generation solar cells. Materials developed at ITAE include **catalysts**.
and membranes for sustainable processes, ceramics and structured components, such as electrode-electrolyte assemblies, for energy conversion purposes. Advanced formulations include metal and metal-oxide nanostructures, e.g. core-shell, biochar, perovskites, transition metal catalysts, zeolites, oxide-based nanofillers dispersed in polymeric matrices etc. (ITAE). The enhanced energy materials and nanostructures have achieved improved efficiency and reliability in electrochemical systems and for the production of sustainable fuels from CO₂ recycling (ITAE).

IMAMOTER synthesizes oxidative nanostructures embedded into a polymer to develop novel flexible, efficient, versatile coatings of easy fabrication and low environmental impact for application in renewable/alternative energy technologies.

In the field of renewable energy, IFP studies innovative semiconductors for use in advanced device for energy production such as solar cells etc. With regard to environmental sustainability, IFP studies “green processes” in the context of the deposition of coatings with tailored functional properties to decrease the impact of the wetting chemistry. Perovskites are also produced at IMEM by vacuum flash evaporation to improve their usability in multilayer devices.

Heterogeneous photocatalysts are developed at ITC for their depollution activity in air and in water. The gas/solid phase depollution activity is assessed in true environmental conditions.

In general, energy materials are actively studied to advance in sustainable/renewable processes, to facilitate system integration and simplification while providing a perspective for market uptake of the most advanced technologies within 5-10 years.

2.3 Advanced materials and nanotechnologies for bio-medical use

IMAMOTER develops composite materials for biomedical applications. Their expertise covers the field of oxidative materials for dental prosthesis and the synthesis and characterization of polymer composites. This knowhow can lead to the development of oxide reinforced polymers, with reduced rigidity compared to that of bare oxide and with enhanced osseointegration properties with respect to the neat polymer.

Modelling drug release in biomedical devices is carried out at IAC in order to characterize the dynamics of the drug diffusing from a polymeric matrix towards a biological tissue and to identify the characteristic parameters that affect its absorption properties with the goal to optimize its therapeutic efficacy.

Applications for drug-eluting stents, medicated patches, and orthopaedic implants are other relevant topics studied at IAC.

IFAC is active in the development of advanced plasmonic substrates for photonic sensing of markers of neurodegenerative conditions and hybrid materials for photonic theranostics of e.g. cancer and hypertrophy, by the intracellular delivery of genetically-encoded probes and silencers and the use of bionic contrast agents for photoacoustics and thermics. A variety of photonic devices are developed, such as whispering gallery mode resonators and optical fibre nanotips for biosensing, scaffolds for controlled drug release and wound healing or tools for genetic amplification.

IMEM researchers use their expertise on materials for electronics for the development of SiO₂-Cₓ based nanosystems for nanomedicine (NWs for local, in deep-tissue cancer treatment) and tissue engineering (porous bioactive 3D scaffolds for dentistry and NEMS structures for subretinal prosthesis). Particular interest is also devoted at IMEM to advanced magnetic and magnetoplasmonic nanostructures for therapeutic and diagnostic purposes. Self-assembly mechanisms are of particular interest for drug delivery applications. Studies are focused on the chemical nature of self-assembled amino acids on Ag and TiO₂.

In the field of human health, IFP studies plasma processes for sterilization or decontamination in order to support the development of new technologies against the microbial infections.

The IEIIT institute leads advanced scientific and technological research in the fields of tissue engineering by developing scaffolds for bone and articular tissue regeneration. Nano-functionalized substitutes are
developed by using graphene-derived nanomaterials or ceramic nanoparticles to enhance the biomechanical features of the materials without impairing the potential of the implants to promote new tissue formation and regeneration.

3. IMPACT

The ability to design and produce innovative materials and nanostructures with tailored properties to activate and control physical/chemical processes will have a strong influence on economics, energy sector, environment, health & safety with a large expected socio-economic impact.

3.1 Impact of enhanced materials and nanotechnologies on industrial processes

Optimization of magnetic materials at IMEM is crucial for the development of low-carbon technologies that will benefit different strategic sectors, such as hybrid and electric transportation, wind power generation, energy harvesting, refrigeration/air conditioning. Micro/nano structures pave the way to new classes of memories, sensors and smart devices exploitable in important technological sectors, such as ICT, consumer electronics and nanomedicine. Organic electronics and optoelectronics and low-D systems are growing sectors. Their impact concerns environment preservation, development of rare-metal-free devices, compact and efficient electronics, ICT and sensing devices. An increasing role is favoured by the possibility to gain control over fundamental quantum-mechanical properties of materials through advanced synthesis, characterization and modelling at the nanoscale. New deposition techniques and 3D integrated nanoarchitectures will have an impact on thin film solar cells, sensors, superconductors, transparent conducting oxides for multiple optoelectronic applications (IMEM). The power electronic sector represents a key technology to address the challenges of energy efficiency and energy saving in green economy wireless infrastructure, broadcast and communication satellites, power conversion and defence applications (radar). New spectroscopic x-ray detectors will allow manufacturing advanced systems for baggage screening, non-destructive testing, and medical applications (IMEM).

Nanofluids developed by ITC hold strong scientific and industrial interest because of their potential to produce an increase of energy efficiency and a reduction in energy consumption, global warming and pollution associated with heating, ventilation and air conditioning systems, and buildings materials. Nanostructured photocatalytic materials will play a similar role on reducing air pollution.

Studies currently carried out at IAC on fluids have a relevant impact on the capability of inspiring and realizing the design of microfluidic devices for the synthesis of novel porous materials and bio-engineering applications. From a computational point of view, a great challenge is due to the full-scale simulation of microfluidic devices at nanometric resolution.

Metal alloys developed at IMAMOTER by additive manufacturing are expected to grow in the next future especially for aeronautic and aerospace applications. The replacement of conventional lubrorefrigerants will result in a reduction of the environmental impact. Low-cost nanostructured metal oxide sensors for early detection and monitoring of poisonous and hazardous chemicals will allow advancing on environmental security and healthcare.

Physical vapour deposition processes for green coatings, developed at IFP, will eliminate potentially harmful chemicals or hazardous wastes present today in many chemical processes.

The new materials, devices and standards developed at IFAC are of specific interest within the fast-developing markets of biophotonics and lighting and will have an impact on new industrial products.

3.2 Impact of advanced materials and nanostructures on energy and environment

The research on sustainable processes at IRC impacts on relevant aspects of community by providing solutions for energy and environmental applications, meeting the pollution concerns including climate
change issues (advanced sorbents for CO₂ capture, water remediation, DeNOx technology), production of sustainable energy (production of synthetic natural gas, catalytic combustion of CO and hydrocarbons, purification of H₂ streams), health (antibacterial, biocompatible materials) and technological issues (low-cost materials for sensors and bio-organic electronics).

The new materials and nanotechnologies developed at ITAE for the energy system address the strategies of promoting the deployment of new sustainable energy technologies with the following expected outcomes:

- **improvement of the energy supply autonomy** (lower dependency from external energy suppliers);
- **competitiveness** of national companies in renewable power/energy sources; capability to achieve the targets established by the European Strategic Energy Technology (SET) Plan; decrease of pollution, **improvement of air quality** with associated health cost reduction; new environmental friendly and cost-effective solutions for power plants and carbon-intensive industry, new markets and job creation in innovative industrial sectors.

Development and synthesis of metal oxide nanomaterials at IMAMOTER will play an important role on gas sensing in environmental applications and as polymer filler for energy harvesting. The latter will help to engage the global energy demand, by capturing otherwise lost energy. This will be beneficial both for the environment and for the financial performance of companies and households. By using mechanical energy that is otherwise wasted, energy harvesters could reduce energy consumption and associated carbon emissions (IMAMOTER).

**Photonics based tools** developed at IFAC aim to improve the energy efficiency of biochemical reactors whereas hydrogen production by photochemical water splitting will supply in the future a potential renewable fuel contributing to the energy independence of the EU.

### 3.3 Impact of nanotechnologies on bio-medical applications

The development of composite materials for biomedical applications in particular for hard tissues replacement at IMAMOTER will provide a significant cost reduction, thus making such systems accessible to a large number of people for an increase in well-being.

The materials developed at IFAC will give rise to new tools to manipulate light at nanoscale for much more sustainable and effective sensing, diagnosing, treating and monitoring of conditions as neurodegeneration, cancer and hyperthrophy or for point-of-care or homecare solutions.

The field of bone graft substitutes is one of the largest markets in the orthopaedic field, being expected to reach $3.2 billion in the United States, by 2022. The biomaterials with favourable nano- to micro-scale, typical cues fabricated at IEIIT aim at improving the quality of life for patients, thus producing significant scientific, societal as well as economic impact.

**Plasma processes for sterilization or decontamination** at IFP will help to fight against the microbial infections with a positive impact for human health.

Development of functionalized/hybrid materials pursued at IMEM is a key point towards multifunctionality, to improve biocompatibility of implants, drug delivery and biosensing applications in nanomedicine.

### 4. EMERGING RESEARCH CHALLENGES

The emerging challenges that this AP is going to face have already been summarized in the previous paragraphs. More generally, whatever the application field, the future developments cannot disregard a few hot issues. Efforts should be addressed to the development of materials, processes, and technologies that: i) replace the use of Critical Raw Materials ii) limit the energy consumption iii) reduce the emission of greenhouse gases iv) enable innovative solutions in sensitive contexts as healthcare and iv) are a relevant part of the circular economy. These challenges will be addressed by the AP by implementing specific strategies: a) strengthening the multidisciplinary approach b) increasing the critical mass of the research
groups by means of a stronger cooperation, especially among the Institutes involved in this AP c) an easier sharing of relevant scientific facilities and infrastructures d) improving the exploitation of modelling and e) improving coordination activities aimed at a more successful participation in large multidisciplinary research projects.

5. CONCLUSIONS

AP10 focuses on materials and nanotechnologies for three main applications industrial processes, energy and environment, bio-medical use.

The first pillar essentially concerns with magnetic materials, semiconductors, oxides, alloys, multilayers and systems characterized by physical confinement, complex nanofluids and innovative catalytic formulations. These advanced materials and nanotechnologies are used in a range of applications covering magneto-opto-electronics, industrial processes, catalysis, sensors etc.

The second pillar addresses a broad spectrum of innovative materials for application in the energy sector and in sustainable processes. The most advanced formulations concern with graphenics, hybrid perovskites, metal nanostructures, transition metals catalysts, zeolites, nano-fluids etc. This sector is particularly involving research on hydrogen, fuel cells, air conditioning, heating and refrigeration, and solar cells.

The third pillar is covering a range of nanotechnologies for bio-sensing and diagnostic devices as well as materials directly used in solving medical problems, particularly in the oncological sector. The materials range from multifunctional optical and/or magnetic agents, to nanoprobes for non-invasive investigations, to systems for tissue engineering. The developed nanosystems are differently functionalized for e.g. anticancer treatments and intelligent drug delivery.

Modelling and numerical simulation applies to all these different themes offering advanced methodologies to progress in each field.

All these sectors are characterized by emerging challenges, such as the need to avoid/reduce the use of Critical Raw Materials and improve nanotechnologies to achieve cost-effective solutions while allowing for a rapid deployment of the developed systems. Efficiency, reliability and sustainability are relevant aspects to focus the research efforts in the fields of green-chemistry and energy-related processes. Research advances are addressed to innovative materials and nanotechnologies for the reduction of polluting emissions while promoting a circular economy. A roadmap is identified to overcome relevant issues by increasing the critical mass of research groups, sharing relevant infrastructures with wider and coordinated participation in multidisciplinary projects.

A large expected socio-economic impact is expected for the new materials and related technologies affecting economics, improving the sustainability of industrial processes, with beneficial effects on the energy sector, on environment, on health & safety.
AP11 TECHNOLOGIES FOR THE USE AND PRESERVATION OF CULTURAL HERITAGE

EXECUTIVE SUMMARY

This is a summary of the first white paper on the activities carried out by the nine Institutes of the DIITET Dept. contributing to the area “Technologies for Cultural Heritage (CH) Use and Preservation”.

On 10 May 2018 the DIITET Director appointed a two-person panel for writing the white paper. A first draft was completed on May 17th and distributed for comments and inputs to the researchers of the involved Institutes. All those inputs were incorporated in a second draft, updated through a participatory process and revised into this version, submitted to the DIITET Director on June 12th.

The opportunities offered by modern technologies for the use and preservation of tangible and intangible cultural heritage are practically unlimited. DIITET’s contributions have been organized according to three main themes of Cultural Heritage - documentation/diagnosis, representation and dissemination - whose interdisciplinary nature requires a collaborative approach that can go beyond our departmental Institutes. The state of the art of these relevant areas is therefore presented in the 1st chapter, further detailing the status of these areas by means of several topics.

The 2nd chapter describes activities and results in each topic, making explicit notice to the DIITET institutes where the activity is taking place.

The 3rd chapter presents the current impact at scientific, industrial, social and political level, considering both national and international perspectives, through: CH conservation and restoration projects; participation in expositions and museum installations; collaboration with companies; social impact projects; collaborations with international institutions.

The 4th chapter describes some emerging research challenges.

The article ends with a conclusion chapter and two annexes: the list of reference persons and a description of further aspects or data (relevant facilities, list of personnel, details about active projects, videos, and images).

1. STATE OF THE ART OF THE RELEVANT SCIENTIFIC AREA

The opportunities offered by modern technologies for the use and preservation of tangible and intangible cultural heritage are practically unlimited. DIITET’s contribution addresses three of the main themes of cultural heritage - documentation/diagnosis, representation and dissemination - whose interdisciplinary nature requires a collaborative approach that can go beyond our departmental Institutes.

1.1 Documentation

This section presents the scenario of methodologies and technologies (HW and SW) for digitizing the shape characteristics or the material/surfaces properties, or for diagnostic analysis of the conservation status, up to sampling intangible CH assets - a mandatory first stage for any computer-assisted management of CH assets.

Small-Large Scale Digitization

Active 3D scanning systems based on laser or structured light offer extreme accuracy and data sampling density. Modern photogrammetric solutions (3D from standard 2D images) offer now performances near to the ones of active scanning. Other 2D digitization solutions via flat scanners, Reflection Transformation Imaging (http://culturalheritageimaging.org/Technologies/RTI), panoramic/360 images or videos are now
widely available. Besides "visual aspect", digitization technologies can exploit non-visible bands of the spectrum or other kinds of radiation, thus providing information about the history and the present status of a CH object and allowing to access the object without invasive analysis.

Processing algorithms and tools for the efficient production of high-quality digital models reached a very good status (with both commercial and open source solutions), even if the automatic ingestion of high-resolution digital data into archival museum systems is not yet a fully consolidated practice.

**Materials and Conservation Status Sampling**

CH applications require instruments for sampling the reflection properties of the surfaces (e.g. color, hyperspectral imaging data or bi-directional surface reflection models) or for investigating the chemical and material composition of artworks by analyzing their interaction with suitable probing radiations (hyperspectral imaging, imaging spectroscopy, X-ray, ultrasound, laser induced fluorescence, etc.). All these technologies should be as non-invasive as possible and should sample both the surface and the inner layers. The results help understanding the execution technique, assessing the conservation status and supporting the restoration.

Miniaturization and cost reduction make also possible to disperse a number of sensors on the surface of an artwork, to sample the environmental and conservation conditions over time and transmitting data to a remote data integration and visualization unit, thus improving risk-based decision-making processes for preventive conservation actions.

**Drones-assisted inspection**

Unmanned vehicles, or drones, working either in air or underwater, improved considerably our sampling capability. These devices offer advantages in speed, safety and cost of acquisition, also allowing the user to inspect areas that are difficult to be accessed. They also allow extending the sampling scale and scope (from satellites to small drones) and allow performing cost-effective and regular monitoring of CH sites.

1.2 Data Representation and Understanding

The sampling technologies available produce data in multiple formats, which have to be mapped to a common space and treated in an integrated manner. Moreover, data and metadata have to be archived; technology supporting data sharing and efficient multi-modal searches should be provided, to make those data the basic building blocks for consultation and reuse for study and further processing purposes.

**Data Mapping and Archival**

The many different classes of sampling devices and/or multimedia resources make data integration a very complex problem in managing tangible and intangible heritage, as those resources cannot be analyzed in isolation. Therefore, we need technologies for mapping all those data in a common space, documenting them with metadata, and supporting permanent archival.

Knowledge management is fundamental to foster the interoperability and re-use of information among actors having different cultural background and skills, which usually deal with cultural resources separately. Knowledge models formalized in ontologies provide a valid semantic base for annotating resources and correlating different complex data (in term of heterogeneity of content, number of documents and media typology) related to a specific product over time.

**Data Search and Exploration**

Features search, a basic component of any data management system, has already been applied to the CH field, providing effective solutions and solving similarity queries over large archives of visual data. Indeed, querying by images helps both in education and research and enables the exploration of inter/intra cultural relationships.
An interesting example is the Google platform (https://artsandculture.google.com) to search CH collections, which indicates how advanced search mechanisms could be used to explore and interact with large Museum collections. However, multimodal and content-based visual search of CH collections is still at its infancy.

**Computer-based simulation**

The availability of innovative mathematical models, numerical methods and information technologies makes possible the structural analysis of historical buildings through of numerical codes. Whereas numerical simulation, which supports the choice and design of strengthening operations, structural health monitoring, relying on the measurement of deformation and environmental vibrations of structures, allows to assess their behavior over time.

**1.3 Dissemination**

Annotated CH resources and visual data have a great potential for dissemination to the public and supporting museum and tourist applications. Intense research is active on those themes and great opportunities are open for technological transfer.

**On-line Data Visualization**

Data visualization has a leading role in both data analysis tasks and for the presentation to the public (including design of museum installations or for didactical uses). The specificity of CH applications suggests high-profile requirements in terms of accuracy and resolution of the 2D/3D representation. The research efforts are focused on the design of efficient and performant SW solutions for rendering those data at interactive rates, keeping data quality and accuracy as unaltered as possible.

The web became the main channel for data distribution and search; this is also true for CH applications and has created the need of revising the visualization technologies, taking into account data transmission needs, view-dependent rendering and on-demand transmission of the data.

**Virtual, Augmented and Mixed Reality**

Interactive fruition of data is now possible by accessing the web with mobile devices, as well as by using specialized visualization devices, very useful for applications in museums, archaeological sites and historic urban contexts.

Virtual Reality (VR) technology has recently been revitalized with the introduction of high quality and low-cost head mounted displays. Augmented Reality (AR) technologies also offers intriguing capabilities for adding knowledge/information in a very natural manner using mobile devices.

The current activities also concern the design of effective interfaces, based on either gestural input or tangible interfaces, allowing untrained users to navigate easily the virtual/augmented worlds, as well dialoging with the environment.

**3D Fabrication**

Technologies able to transform a 3D model in a physical instance have also boomed in the last decade, thanks to the huge interest in industrial applications (Industry 4.0). This raised also a lot of interest in CH, to either populate museums expositions with static and enhanced/sensorized replicas, to support restoration projects, or to improve the impaired people perception experience.

**Serious Games**

Computer games with educational purposes are becoming popular as a funny way to engage the public into an active state of learning rather than to receive information passively, through several factors as storyboard, graphics, usability, collaboration/competition mechanisms and interaction devices.

Serious Games have the potential to recreate accurately an historical setting, providing a holistic experience including sounds (spoken language, traditional music), aesthetic elements, folkloric and religious events, and
giving the opportunity to practice behavioral codes and habits through in-game tasks, thus offering a strong contribution to preserve the intangible heritage.

2. CONTRIBUTION TO THE RELEVANT SCIENTIFIC AREA

CNR activities and results in relevant areas are here presented, following the organization in topics presented in the previous chapter and making an explicit reference to the DIITET institutes where they are taking place.

2.1 Documentation

Small-Large Scale Digitization

[INM]
- Innovative and unique tool for remote sensing and applications to the territory and related resources based on multispectral investigation (102 investigative bands) with the fine radiometric discrimination (up to 0.02 micron push) typical of the MIVIS sensor used for aero-transported remote sensing (spatial resolution up to 3 m x 3m).

[IREA]
- Synthetic Aperture Radar systems (SAR) on satellite platforms for 3D reconstruction and long-term monitoring of deformations on large areas;
- Georadar and holographic radar for high-resolution imaging of underground and inner parts of structures and artworks (detection/characterization of defects and construction modalities, buried/hidden ruins), used in Pompeii and Herculaneum.

[ISTI]
- Active (laser-based, structured light, ToF, RGBD) and passive (structure from motion, photogrammetry) methodologies for 3D digitization.
- Design of 3D digitization systems and of the required post-processing software algorithms and tools.
- Intense algorithm design activity, producing many innovative solutions and a leading open-source tool for sampled data processing (MeshLab, http://www.meshlab.net), distributed worldwide, with around 400,000 downloads/year, considered as a major resource by the CH community).
- Contribution to the design of innovative technologies for Reflection Transformation Imaging (RTI) acquisition and processing.

Fig. 1 - Example of hyperspectral image scanning at the Picasso Museum (Barcelona, Spain).
Materials and Conservation Status Sampling

[IFAC - METEORS group]
- Optical-fiber coupled LIF spectrometer for in situ measurements aiming at characterization of biofilms
- Fluorescence LIDAR imaging systems (4D data: 3D hyperspectral fluorescence images and fluorescence lifetime) for the remote diagnostics on monumental surfaces.
- Integration of 3D models and fluorescence hyperspectral images.
- Studies on the effects of low-fluency laser radiation on mural paintings.

[IFAC - SABeC group]
- Design and assembling of hyperspectral imaging devices
- Optimized dedicated software and data processing procedures, including image-cubes mosaicking, new methods for pigment identification and mapping, visualization, and archiving of the results.

[INM]
- Development of contactless vibro-acoustic techniques and devices for the structural decay processes diagnostic of painted surfaces (frescoes, glazed ceramic tiles, panel paintings).
- Development of an Audio Frequency - Acoustic Imaging (AF-AI) technique providing frequency resolved acoustic images of paintings.
- MIVIS hyperspectral data (0.43-12.7 micron) processing to automatically characterize and quantify elements and materials in geographically identified areas
- Development of reproducible methodologies on a large scale, with cartographic restitution, as well as the integration of some other data (remote sensing, cartographic, ISTAT, etc.) in GIS and WebGIS.

[IREA]
- Development of optic fiber sensors for in-situ distributed monitoring of deformation and/or temperature on long distances with high spatial resolution
- Experience in THz imaging (to sample overlapping layers and delamination phenomena) and spectroscopy.
Digital processing and analysis of multispectral images of ancient documents to highlight their status of conservation and help possible material restoration plans.

Deployment of sensor networks to monitor the structural health of historical buildings.

Drones-assisted inspection

An inter-laboratory facility to design and use drone-based technologies, including a drone setup to capture data for 3D reconstruction and monitoring crack patterns in historical buildings.

An embedded card allowing the drone to self-locate during the survey.

SLAM-based methods to improve the pilot front-end experience, including real time visualization capabilities, and to support the drone navigation self-awareness. The 3D model of a cultural heritage asset is thus made accessible on-line, along with the acquired and processed data describing its structural status, experimented in Pompei.

Combined use of drone and multicamera system for realizing 3D model using SfM techniques, experimented on an historical village.

2.2 Data Representation and Understanding

Data Mapping and Archival

Analysis of multi-dimensional data for visualizing the temporal changes of urban artefacts and monuments over time by investigating the variables that are not directly observed, depending on their own characteristics and the impact on the environment.

Development of a new hyperspectral image data processing focused on the identification and mapping of spectral features of selected pigments/dyes

Providing access to the corpus of digital data sets through a unique and user-friendly web platform specifically designed for museum professionals, aimed at facilitating exploitation of massive and structured data sets (CRISTINA - CNR Retrieval of Images from hyper-Spectral data Through Interactive Network Access).

Several spectral databases, produced by analyzing in the UV-Vis-IR ranges diverse artists’ materials and techniques, freely accessible on the web.

Web-site prototype for visualizing and accessing spot reflectance measurements and hyperspectral imaging data developed with the Uffizi Gallery.

Knowledge management system based on a) semantic enrichment of metadata to increase the level of description (semantics, workflow provenance, quality); b) data integration, according with the Linked Data principle of the web as “global space”, with the study of algorithms for the semantic analysis of resources and methods to explore such datasets.

Methods and tools to support the whole 3D annotation pipeline (format for 3D annotated models; annotation transfer across models) and shape analysis workflows (feature detection and characterization - patterns, decorations, and style traits).

Dashboard platform including a novel automatic processing pipeline, based on the IMATI GRAVifix library, which prepares 3D models for ingestion in curatorial and analysis systems (repairing, simplification, data organization).
Design of tools for the virtual restoration of damaged documents to help paleographic analysis.

Design of systems to support data documentation and integration, including also features for mapping data on a common representation space and providing visual analysis functionalities, applied to the restoration of the Neptune Fountain of Bologna, developed for ISCR, Bologna University and Bologna Municipality in 2017. It allows restorers to work cooperatively through a web-based documentation system, where all the data are mapped, indexed and searched over the 3D digital representation of the artwork surface, supporting the creation of technical drawings and maps directly on the skin of the artwork. It is a very first example of restoration documentation implemented in real-time on a web-based 3D system.

Design of systems supporting the documentation and analysis of archaeological findings by a mobile device allowing the automatic shape recognition performed on a remote archive and its documentation on the remote archival system.

**Data Search and Exploration**

**[IMATI]**

- Multimodal information systems, tailored for museums and tangible/intangible CH collections, integrating innovative search and browsing paradigms to support users in information discovering.
- Methods for automatic feature extraction (visual/mood attributes or keywords) and for semantic annotation - from text, images, 3D, audio, video related to tangible and intangible resources - allowing users to query the art collections based on their visual or semantic content.
- Development of methods libraries to index, retrieve and classify 3D models focusing on multimodality and query formulation mechanisms (**data search and retrieval or similarity queries** over large archives of visual data, recognition based on global characteristics, salient parts/features, and also properties related to color or and textures).

**[ISTI]**

- Searchable CH object repositories (metadata schemas, administrative and descriptive metadata plus additional entities for searching on both contents of and relationships between the archived documents);
- Tools for the extraction of semantically significant visual descriptors (features) to support visual search paradigms;
- Systems supporting cross-media search on raw digital content (text queries to retrieve relevant non-annotated visual digital content).

![Example of semantic annotation taken from the Gravitate Dashboard.](image)

**Fig. 4 - Example of semantic annotation taken from the Gravitate Dashboard.**

**Computer-based simulation**

**[ISTI]**
- Development of mathematical models and software for the structural analysis of ancient masonry constructions. In particular, the Finite Element (FE) code NOSA-ITACA (freely available at [www.nosaitaca.it](http://www.nosaitaca.it)) allows for modeling the nonlinear behavior of masonry constructions under static and dynamic loads, by taking into account the material's inability to withstand tensile stresses.
- Numerical strategies for FE model updating, aimed at calibrating a FE model of a structure in order to match numerical and experimental results, and damage detection techniques

**[IAC]**
- Mathematical models and simulation tools for the study of chemical and biological damages, such as degradation on porous stones caused by salt crystallization, contact with iron compounds, and for the description/prediction of the flow of incoming/outgoing visitors in outdoor/indoor areas, including parking points of the museum area.
- Image processing for automatic degradation detection (alterations and colorimetric/geometrical properties) and for restoration of digitized copies of archive material.
2.3 Dissemination

On-line Data Visualization

[IMATI]
- Visualization tools providing users with a compact overview of the available data, in order to mine properties and relations among data and to achieve a correct interpretation of the results, using thematic paths to support a personalized exploration of the archive.

[INM]
- Methods for the implementation of WebGIS Platforms, characterized by immediacy and ease of use, aimed at non-expert users, enabling to share information in real time, allowing the management of the multiplicity of information / data, and making complex evaluations (e.g. for monitoring and control of the land).

[ISTI]
- 3DHOP (3D Heritage On-line Presenter), an open-source platform for supporting users in the publication and visualization of 3D content on the web; it includes an extremely efficient web-based rendering engine (multiresolution encoding, data compression, progressive transmission, view-dependent rendering), different interaction approaches and sophisticated visual data analysis features. It counts hundreds of users and thousands 3D content published on the web.

Fig. 6 - Some examples of web-based visualization of 2D-RTI and 3D data.
[ITC]

- Development of multimedia interactive map based on a single HTML page using AJAX, with a client-side control mechanism using jQuery components and open data format GeoJSON. The user can select a landmark viewing its multimedia content previews in as scrolling window or in a gallery; landmarks—visualized with multi-shape markers using unambiguous colors—could be filtered through their categories and types, accessibility status and time line, thus improving the system usability (www.itc.cnr.it/ba/map).

![Example of multimedia interactive map](http://www.itc.cnr.it/ba/map/BRI)

**Fig. 7 - Example of multimedia interactive map (http://www.itc.cnr.it/ba/map/BRI).**

Virtual, Augmented and Mixed Reality

[IASI]

- Methodological approaches and innovative technology (App Based Indoor/Outdoor, Proximity Analysis, Efficient Path Profiling, Augmented reality) that while not renouncing the rigor of historiographic research, improve learning, access and use of CH

[ICAR]

- Augmented reality, virtual reality and body tracking technologies solution development.
- Design of “touchless”, multi-degrees-of-freedom user interfaces, for both virtual and augmented reality applications, by using depth sensors and/or RGB cameras, relying on algorithms to filter depth data and to increase the precision of distal pointing and of skeletal tracking.
- Conversational chatbots based on knowledge-graphs.
- Usability evaluation campaigns, both considering qualitative and quantitative data.

[ISTI]

- Experience with modern VR/AR technologies applied to interactive presentation of CH assets on land/museum and underwater. Use of head mounted displays to enable an augmented presentation of 3D printed replicas.

3D Fabrication

[ISTI]

- New solutions for the production of resin copies by molding, thus reducing cost and increasing production speed.
● 3D fabrication technologies for the design of artistic reproductions.

Serious Games
[IMATI]
● Study of the game mechanics having an impact on learning in the context of CH, focusing on the representation of 3D worlds in role-playing games and 3D setting and immersive technologies to facilitate engagement, a feeling of presence in the digital environment, empathy with the game characters and learning.

Fig. 8 - 3D fabrication as an option to close the loop: physical - digital - physical.

3. IMPACT

Participation in major CH conservation and restoration projects
Research labs contributing to AP11 have been partners or technology providers in a very large number of conservation and restoration projects, collaborating with primary conservation institutions, such as:
● Istituto Superiore per la Conservazione e il Restauro - ISCR, Rome [ISTI, IAC]
● Opificio delle Pietre Dure - OPD, Florence [IFAC, ISTI]
● Venaria Reale, Torino [IFAC]
● CH Superintendencies and Museums (Galleria Accademia Firenze, Uffizi, Museo San Marco Firenze, Opera Primaziale Pisana, Galleria Borghese Roma, Museo di Archeologia Ligure, Archivio storico della Fondazione Ansaldo) [IFAC, IREA, ISTI, IAC, INM, IMATI]
● Archaeological sites: Pompei [IREA, ISTI], Ercolano [IREA], Casale di Balsignano [ITC]
● Museums abroad: Museum Picasso, Barcelona, Spain [IFAC], Gallery of Art Washington DC, USA [IFAC], British Museum, London, UK [IMATI], Cyprus Museum [IMATI], Guggenheim, New York, USA [ISTI], Museu Nacional d’Art de Catalunya, Barcelona, Spain [ISTI]
● Historical city centers: Gubbio, Matera [IREA], Cetinje (Montenegro), Matera, Siracusa, Tirana (Albania) [ITC]
Participation in expositions and museum installations


- Exhibition “Il Bello o il vero” - Napoli, Complesso Monumentale San Domenico Maggiore, February 3 – June 6, 2015 – Design and implementation of a system for the interactive visualization of 3D reconstruction of statues [ICAR]

- “Alchemy by Jackson Pollock”, Temporary exhibition, Guggenheim Venice, Italy (2015) and Guggenheim Museum, New York, USA (2017) [ISTI]

- Museo delle Ceramiche di Grottaglie [ITC]

Collaboration with companies (technology transfer)

- [IFAC – SABeC] SABeC group selected in 2016 by SPECIM Spectral Imaging Ltd. (Oulu, Finland) as a pilot laboratory to test and check the IQ prototype performances in the Cultural Heritage fields.

- [IMATI] Collaboration with Softeco, for the project on the Ansaldo Foundation business Industrial Heritage archival Archive

- [ISTI] Contract with HP (US branch) for right of use of ISTI VClab 3D graphics libraries.

- [ISTI] Long-lasting collaboration with TEA-Sas, Catanzaro, Italy, for a series of European and National projects on analysis, virtual restoration and archival of digitized CH assets, such as paintings and ancient/degraded documents.

- [IAC] collaborated with Fratelli Alinari photographic archive in Florence for the development of novel digital restoration tools

- [IREA] collaborates with Leonardo and e-GEOS for the development of a ICT platform for effective resilience of CH based on the synergic use of several sensing technologies.

Social Impact Projects

- [ITC] “Vi.S.T.A. Virtual and Social heritage Tour Application” project for developing and testing an integrated technological system for virtual and social touring of artistic and cultural heritage managed by the “Polo Museale” in Apulia Region.

Collaborations with international institutions

- CNR colleagues [IMATI, ISTI] have been regularly invited to the workshops organized by the EC for discussing the themes of forthcoming calls (e.g. ICT and Cultural Heritage Workshops organized by CNECT, G2 and held in Luxembourg in 2016 and 2017). Participation in these events was by invitation only (selected experts).

- CNR leads the EUROGRAPHICS Working Group on Graphics and Cultural Heritage and is regularly present in the program committee of the yearly associated EUROGRAPHICS workshop on Graphics and Cultural Heritage (GCH). The 2018 edition will be in Vienna, Austria (Visual Heritage 2018, http://2018.visualheritage.org/)

- CNR has been among the organizing partners of the IEEE Digital Heritage 2013 and Digital Heritage 2015 conferences, a large event attracting >500 registered participants (R. Scopigno Co-Chaired the IPC in 2015).

- IFAC-CNR is actively involved in running the international Infrared and Raman Users’ Group (IRUG), which is dedicated to the support and professional development of its members by providing a forum for the exchange of infrared and Raman spectroscopic information and reference spectra for the study of the world’s cultural heritage (www.irug.com, M. Picollo chair for Asia-Australia-Oceania).
● CNR colleagues are involved into the program committee of many international conferences concerning ICT & CH themes (e.g. the European Geoscience Conference, where several sessions are devoted to CH since 2010; IEEE VSSMM; EG GCH; CAA; Digital Heritage; etc.).

● R. Scopigno [ISTI] is Editor in Chief of the ACM Journal on Computing and Cultural Heritage.

● CNR colleagues are members of Editorial Board (Editor in Chief and Associate Editor) of HERITAGE, an open access journal of MPDI

4. EMERGING RESEARCH CHALLENGES

● Novel methodologies for the integration and correlation of multi-sensor data to perform multiscale, multi-resolution and multi-depth analysis to provide enhanced understanding and to support risk-based decision-making. Advancements of artificial intelligence algorithms for visual analytics and data characterization.

● Novel portable solutions for 3D acquisition of objects with not-cooperative surface reflection properties.

● Miniaturization of complex diagnostic instruments and related costs reduction, e.g. using technologies based on fluorescence and reflectance hyperspectral imaging systems; design of systems based on radiofrequency electromagnetic field for contactless disinfection of artifacts from molds and lichens.

● New ways of accessing and exploring archival resources, overcoming cultural barriers and data types differentiation, exploiting semantic to link resources; innovative methodologies for the annotation and browsing of resources (visual and textual searches); exploiting CH knowledge models codified in ontologies to allow a search for concepts; semantically annotated 3D models.

● Automatic methods to characterize and even discover similarities in style, supporting a more effective exploration of digital collections; associations between pieces which can be part of different collections; identification of common production patterns.

● Long-term, continuous structural health monitoring and real-time damage detection techniques, data-driven analysis, algorithms for improving efficiency and reliability of numerical codes for structural analysis.

● Moving from an artefact-oriented to a context-oriented perspective in the modelling, representation and management of CH data and information.

● Integration of gesture/tangible/speech interaction and augmented/virtual reality, dialoguing with IoT sensors and optimizing user interaction capabilities; development of sensorized, active replicas to support AR applications.

● Extending GIS or BIM technologies to support the specific needs of CH built environments, addressing documentation, representation, mapping, modelling and promotion of assets.

● Development of tools with interfaces accessible for all, with the aim to support schools, stakeholders and small communities in acquiring and sharing knowledge on minor/local assets using low-cost devices and open data repositories, boosting the sense of belonging to a common cultural heritage of local communities.

● Development of GIS technologies for Cultural Heritage and built environment, addressing at the same time documentation, representation/mapping/modelling and promotion of assets, focused on network patterns among territorial markers and minor resources, performance enhancement criteria and ‘towing strategies’ on a regional scale.

5. CONCLUSIONS

This paper presents the technologies for the use and conservation of cultural assets developed in the last few years in the Project Area #11 (AP 11) of DIITET. Some of these technologies have been designed focusing on the needs of potential users, ranging from experts (art historians, curators, conservators, conservation scientists, restorers, archivists) to general users (museum visitors, students, public).
The current state of AP11 is quite good as far experience, critical mass and national/international visibility are concerned. Some facts and figures substantiate this assessment.

AP 11 is contributed by several institutes (we list a detailed list of the personnel involved in Appendix 2) and has reached a considerable critical mass, with 376 PM contributed by 80 researchers (see the data presented in Annex 2); these PM correspond to 34 research units at full time, which is the size of an average CNR Institute. We consider these figures as a considerable critical mass dedicated by CNR to the theme ICT & CH. The estimated personnel cost is 1.590.000 Euro (this total is computed by taking into account only the cost of the permanent staff, since the staff with temporary contracts is financed by external projects).

Another important indicator is the capability of a research domain (and the researchers involved) to secure funds on competitive research project calls. Appendix 2 presents the list of the research projects active to date, all of them financed by external competitive calls. We are proud for the number and quality of those projects. The total of the funds secured on those competitive calls is 6.031.000 Euro on an average 3 years duration (thus, 2.010.000 Euro per year).

Assuming the estimate above of the human power dedicated, activities in AP11 return a multiplier factor of 226%. This figure is higher than the average CNR and demonstrates the value and profitability of the research on ICT & CH done at CNR.

The themes in AP11 are therefore active, presents open issues for basic research in ICT, and are backed by a domain, which is an excellent field for assessment and dissemination of new technologies. Moreover, this is a domain where CNR is already fulfilling very well his third-mission role (especially towards CH institutions, museums and in applications oriented to tourism). Impact over industry is still limited (due to the scarcity of resources dedicated to the management and fruition of CH at the national level, which still do not make this domain very attracting for companies); but all indicators show that this situation could change shortly, especially for a country like Italy so much involved with tourism and cultural industry.
EXECUTIVE SUMMARY

Space exploration and Earth Observation have always fascinated man pushing his knowledge needs. The consequence has been the ever increasing technological development of airborne and space borne platforms, satellites for communications, instrumentation for space and Earth observations in a broad range of the electromagnetic spectrum with active and passive sensors.

Aerospace and Earth observation have always played a fundamental role in CNR. CNR is in fact accredited by sector specific studies at levels of international scientific excellence in the field of remote sensing; CNR researches are involved in several projects that concern the exploration of space and aeronautics. There are many collaborations between CNR and such space agencies as ASI, ESA, NASA, JAXA, CNES, DLR, CSA, to remember only the main ones and CE.

The Project Area (PA) has the objective of coordinating the CNR activities of the sector, of encouraging the development of innovation, research and experimentation activities, as well as maintaining and increasing the interaction with the space agencies and the industrial component, in line with the priorities defined by CE.

The main concern of the PA regards the development of the many technologies devoted at exploring the space and the Earth. Such technologies can be categorized as upstream and downstream. The former regards sending objects into space and space exploration and push the provision of technology. The latter exploits upstream for a range of different applications such as satellite broadcast services and Earth Observation and is the motivation to develop algorithms and methodologies.

The activities encompass security in space, technologies for space exploration and space telecommunications, aeronautics and navigation, Earth Observation (OT) technologies and ICT tools. With reference to EO, the skills are broad and cover sensors operating from the optical band up to the microwaves and gamma rays of cosmic origin, electromagnetic modeling and statistical data analysis with the ICT technologies and infrastructures for their management, processing and representation.

All the activities of the PA appear well established and well connected within the context of international research and technology.

1. STATE OF THE ART OF THE RELEVANT SCIENTIFIC AREA

Research and development for aerospace and Earth observation technologies is an extremely wide area, embracing a wide number of topics in the forth-and-back path involving the upstream segment, for the development of the enabling space infrastructure (launchers, platforms, sensors, etc.), and the downstream segment for the development of products and services.

As access to space is costly, involves technical risks, use of cutting edge technologies and longer times for both project development and return on investments, the sector has been traditionally government dominated by applications to environmental risk monitoring and security.

The viability of space-enabled services requires, as matter of fact, markets of large users. Notwithstanding, the increasing number of private entities currently engaged in space activities is gradually operating a shift in the traditional roles of public and private sector. This is testified by always more frequent use of the terminology “space economy”, that is the full range of activities and the use of resources creating value and benefits to human beings in the course of exploring, researching, understanding, managing, and utilizing space.
The importance of space as a privileged place from which to observe the Earth in order to know, understand and tackle important processes that impact on man life is easy to understand. Space is however not an easy environment, hard for technology.

Issues related to safety and the need to develop cutting-edge technologies have always been inextricably linked to space efforts. A central topic concerns the safety of space activities, both in orbit and in cases of uncontrolled reentry. The main aspects of current activities and future trends comprise modeling, mitigation and remediation of orbital debris; prediction of uncontrolled reentries in the atmosphere for civil protection purposes; spacecraft splashdown; astrodynamics applied to the support of space missions, scientific experiments, tracking systems and orbital determinations.

Similarly, technologies for the production and storage of energy and technologies for the space observation from the space are also of key importance especially for space exploration research.

The development of satellite telecommunications technologies, with particular reference to the next-generation High Throughput Satellite telecommunications networks is a key aspect. The activities cover the different network levels, from the study of architectures and protocols up to the modeling of the transmission channel and the design, implementation and experimental characterization of microwave components passive and active in the range of millimeter waves. Regarding to SW technologies, multiple satellite access protocols, protocols for delay and disruptive tolerant networks (DTN), future web technologies, M2M protocols via satellite and Information Centric Networking paradigms for sensor web applications, drone networks, UAVs and RPAS and communication protocols in Line of Sight and beyond Line of Sight are relevant.

Technologies for aerospace, with particular reference to power generation systems with low environmental impact, structural monitoring, safety in aeronautics, ditching, and maintenance and management of the end of life are also relevant.

Earth observation (EO) is experiencing an astonishing growth, deeply affecting both research as well as commercial outlets. To perceive the importance of this topic, it is sufficient to browse for the EO programs currently running at international level in the majority of the developed countries. Limiting to Europe, the Copernicus program is for instance playing a key role for the development of information services in several application domains. The Sentinel program, with the launch of six different families of sensors, is implementing what is referred to as “the European Observation Capability”. In parallel the Copernicus Accelerator, EO is boosting the growth of market oriented services and huge technological transfer from research to business. At the national level, the technological development of the COSMO-SkyMed constellation, currently in orbit, the COSMO-SkyMed Second Generation and several other programs such as PRISMA, gives to Italy a key role in the EO international arena.

New challenges are being addressed, the most exciting future trends being related to the development of small satellites, which are going to enable the availability of wide constellations as well as satellite formation, capable of improving revisiting time, site access and, above all, providing advanced observation diversity. Such an advance will reflect also in the need of improving R&D in the whole value added chain that goes from the data acquisition up to the serviceability levels.

Improvement of services oriented to the different application domains asks for advances on one side of methods for the statistical analysis of the EO data, including data fusion algorithms and methods for EO data interpretation, on the other side for improvements in the electromagnetic modelling. The latter is crucial for the development of retrieval algorithm to derive bio-geophysical variables for environmental monitoring and risk prevention.

During the last years, EO data have been steadily growing in volume and typology, and improving in terms of ground coverage, revisit time and spatial/spectral resolution. This provided new opportunities for application development, which, in turn, required innovative and improved methodologies for electromagnetic and statistical modelling of these new EO datasets (e.g. time series covering long periods with high temporal sampling). For instance, a great attention has been devoted to novel data fusion approaches as well as to
automatic techniques able to manage large amount of data, and to extract useful information by them (e.g. deep-learning algorithms represent the newer trend in the EO big data analysis.

ICT infrastructures have led to disruptive technological advances with terrific societal implications. Topics concerning the study and development of techniques for the use, analysis and processing of Earth Observation (EO) data, and corresponding geospatial information, based on the use of advanced ICT platforms are therefore becoming more and more important. In particular, the recent availability of a huge amount of satellite data (with particular reference to those acquired on a global scale by the Copernicus Sentinel sensors) and the increasing availability of data from ground-based sensors has opened new research scenarios focused on effective and efficient processing of EO data to obtain information of the Earth’s surface at very large spatial scale and in extremely short times. To this end, the use of high-performance computing infrastructures, the development of specific algorithms for processing EO data, along with the possibility of efficiently sharing these data through standardized services, becomes of central importance.

Five main topics can be identified considering the competences and skills available in CNR in such a huge area as Aerospace and EO: Space technologies and Space Safety; Space communication and aeronautics, Earth Observation Technologies; Model based data interpretation; ICT tools for the management, processing, representation and exploitation of EO data.

2. CONTRIBUTION TO THE RELEVANT SCIENTIFIC AREA

Space technologies and Space Safety

Space Safety. Modeling of space debris for the impact risk assessment in orbit, for the identification of operational procedures, standards and technologies minimizing the production of new debris, and for the evaluation of the effectiveness of technological solutions allowing the active removal of objects abandoned in space. The main objectives are to guarantee the functionality and safety in orbit of manned and unmanned systems, and the preservation of the space environment.

Space Systems Control and Astrodynamics. Studies and tests of spacecraft splashdown; orbital analysis for the support of space missions, with and without crew; study and modeling of non-gravitational perturbations to support fundamental physics experiments in space; orbital determination starting from radar, optical and laser observations; activities in the area of Space Situational Awareness (SSA) and Space Surveillance and Tracking (SST).

Optoelectronics, Aerospace Sensors and Power Technologies. Test systems for star trackers and of innovative compressive sensing-based prototypes using advanced optoelectronic technologies, such as micro-mirror arrays and LCD. Technologies and processes for power generation and energy storage: devices in configuration fuel cell plus electrolyzer and their integration into a single device (Regenerative Fuel Cell) for closed-loop energy generation, i.e. without emissions, being therefore suitable for the planetary robotic exploration and for energy self-sufficient space stations.

Technologies for the Observation in Space. Systems for focusing and spectral detection of X and gamma rays from cosmic emission through high efficiency lenses based on diffraction and 3D spectral detectors in the energy band. These capabilities made possible the characterization of the Gamma-ray Burst Monitor (GBM) instrument of the CALET (CALorimetric Electron Telescope) experiment, deployed aboard the International Space Station (ISS), through simulations and data analysis of measurements of the photon bursts incident on the apparatus.

Space communications and aeronautics

Space Communications. Development of technologies for satellite payloads, avionics, Unmanned Aerial Vehicles (UAVs), Remotely Piloted Aircraft Systems (RPAS), with a particular attention to the next-generation High Throughput Satellite (HTS) systems, massive Machine Type Communication (m-MTC) networks, and Command, Control & Communications (C3) systems. The interdisciplinary skills of the CNR institutes cover different levels, from bread-boarding of antenna-systems and RF front-ends, to the study of architectures
and protocols, to the modelling of the transmission channel, by also considering the design, implementation, and testing of Software Defined Radios (SDRs), Software Defined Networking (SDN) architectures, and Network Function Virtualization (NFV) concepts.

**Aeronautics.** Emergency ditching of aircrafts: development of high-fidelity and low-fidelity computational tools for the fluid-structure interaction during the emergency ditching and support the physical understanding of the phenomena through dedicated, representative experiments.

Sloshing wing dynamics: development of advanced numerical solvers for the prediction of loads and viscous dissipation induced by sloshing fuel inside wing tanks of airplane subjected to wind gusts.

Aerodynamics and aeroacoustics, structural control: computational models for aerodynamics, aeroacoustics and for the structural monitoring in aeronautics

**Earth Observation**

**Microwave technologies.** Space borne Synthetic Aperture Radar (SAR) interferometric techniques for large area monitoring and for the 3D reconstruction and monitoring of complex scenarios such as urban areas. Airborne SAR technologies. Microwave radiometric technologies for the observation of sol, CIMR and MWI instruments.

**Infrared technologies.** Direct and inverse modeling of radiative transport in the Earth’s atmosphere are core activities conducted for remote sounding of atmospheric temperature and composition by nadir/zenith and limb emission measurements from ground-based, high altitude and space-borne platforms in the spectral range from the infrared to the sub-mm and mm waves.

**Optical band technologies.** Lidar high-resolution spectral and temporal systems, Lidar imagers, Lidar 4D, optical hyperspectral systems, image interferometers in VIS-IR. Prototypes of LTA (Lighter Than Air) stratospheric platform instruments. Hyperspectral and LIDAR image simulators. Compression algorithms and blind methods to characterize the quality of the instruments. Customized signal processing methodologies for multispectral, hyperspectral, LIDAR sensors.

**Platforms and integration with in situ technologies.** Integration of remote sensing technologies and in-situ sensing technologies. Processing, integration and fusion of remote data sensed with different technologies, such as optical, multispectral, and SAR sensors from unmanned aerial vehicles (UAV), for smart industry and smart farming applications. Development of prototypes for in situ optical measurements. Measurement campaigns, ground truth campaigns, CalVal activities and management of test sites.

**Model based data interpretation**

**Electromagnetic modelling.** Models for interpreting EO data and retrieving bio-geophysical parameters over bare soils, agricultural and forest vegetation, snow, sea and inland waters. Time series modelling of Synthetic Aperture Radar (SAR) data for retrieving high resolution (e.g. 1km) surface soil moisture at regional/continental scale. Direct and inverse modelling of radiative transfer in the atmosphere for deriving information of its physical properties (i.e. temperature and humidity profile, LWC, pressure, chemical composition, etc.). Atmospheric data correction.

**Statistical Modelling.** Algorithms of signal/image processing, and data fusion (e.g. based on Bayesian Networks, pansharpening and hypersharpening) for information extraction (e.g. ship classification/identification, route prediction). Supervised (data/knowledge driven) and unsupervised methods for data clustering and classification, and for automatic change detection of land use/cover. Inversion algorithms based on statistical approaches (i.e. Bayes and Nelder-Mead neural networks) for estimating bio-geo physical parameters from EO data. Local and global scale thematic maps generation of soil moisture, agricultural and forest biomass, snow cover and snow depth. Statistical methods of multi-temporal (e.g. InSAR time series) and multi-source data analysis for mapping and monitoring natural/man-made disasters (floods, landslides, fires, oil-spills, earthquakes).
ICT tools for the management, processing, representation and exploitation of EO data

Grid / Cloud computing and geospatial data infrastructures. Integration of technologies and systems oriented to archiving, rendering, presenting and processing of geospatial data. Development of algorithms for processing of remote sensing data on High Performance Computing (HPC) architectures (grid-cloud computing). Computation and simulation for EO product generation and applications. Architectures and implementation of infrastructures of interoperable spatial data for research, access, exchange, and processing of geo-referenced environmental and heterogeneous (abiotic and biotic) data. Virtual laboratories for processing of geo-referenced data aimed at studying the territory through the coordinated use of web geo-services. Analysis and processing of georeferenced spatial data to support knowledge, management and planning of environmental resources. Integration and management of multiple ontologies of geospatial information for different application domains, within the framework of relevant standards. Research and development on synergistic use of EO data based on innovative data fusion techniques and assimilation models.

This line of research considers the application of Artificial Intelligence (AI) planning and scheduling technologies to increase the autonomy capabilities of current and future space missions, such as Earth Observation (EO) missions. The focus is on intelligent decision-making, such as the autonomous synthesis of spacecraft activity plans to be executed, thus enabling a spacecraft to safely achieve a set of science goals without a strict human control loop. To provide this capability, AI-based planning, scheduling, and execution techniques can be used to create, optimize and validate spacecraft plans based on a rich model of spacecraft operations. This leads also to investigate mixed-initiative planning techniques when autonomous systems and ground segment personnel are to collaborate for achieving mission objectives. A further step ahead is the design of integrated planning and learning algorithms to acquire new knowledge in (partially) unknown and unstructured environments.

3. IMPACT

Curiosity and knowledge have always been fundamental for mankind. If science is the study of the nature and behavior of natural things it is apparent that space is a privileged place from which to observe the Universe and the Earth to know, understand and tackle important processes that impact on man life. Unfortunately, space is not an easy environment: difficult and expensive to reach, hostile for man, hard for technology. Space is a real challenge.

Not surprising, many issues and competencies are involved in the PA. Instruments have to be conceived, designed, realized, launched and then managed, causing a hard technological impact on the development of such enabling technologies as propulsion, optics, mechanics, electronics, acquisition systems, telecommunication systems, data processing tools, spatial debris de-orbiting.

Modern societies heavily depend on satellite technology, for navigation, communications, meteorology and Earth observation (EO). Space technologies also affect agriculture planning, disaster management, medicine, land monitoring, transportation and are a valid tool for policy makers.

Our PA is fully inserted in the research and development of aerospace and EO technologies and all its activities have important impacts.

CNR space debris mitigation groups coordinate important EU research projects, are leaders in the space debris and represent ASI in the IADC committee. CNR is the leader in providing re-entry predictions of uncontrolled space objects and products specifically tailored for national authorities.

Compressive Sensing (CS) technologies are gaining importance. CNR has recently leaded two ESA projects for space applications, exploring the performance of novel CS-based instrumental concepts.

Optical Ground Support Equipment (OGSE) for testing multi-head Star Trackers (ST) has been recently developed by leading to the implementation of a miniaturized electro-optical device able to generate synthetic images of dynamic star fields for ST testing.
3D CZT spectro-imager module can realize the innovative high performance detectors required by new space instrument for hard X-/soft γ-rays astronomy. The configuration of the device will allow the implementation of a large variety of satellite mission.

Human space exploration, using aerial drones (AUV) for EO or surface vehicles (manned or unmanned USV) for planet exploration, based on electrochemical energy production and storage systems (FC, EZ, battery, etc.) can significantly contribute to Space Technology improvement by collaborating with the main stakeholders for power generation for stationary and surface mobility in space.

5G will deliver important features for of stakeholders, such as ultra-high bandwidth and ultra-low latency, thus enabling new applications like virtual reality and tactile Internet. The initial deployment of 5G systems is expected in 2020 and will bring significant innovations with a capacity 1000 times higher than 4G systems at a reduced energy power.

5G will allow the integration among different network segments. Terrestrial, aerial, and satellite networks will exploit seamless integration thanks to the large efforts still in place to provide such a result. Satellites will address important use causes for 5G-critical communications, i.e., future railway, maritime, and aeronautical communications.

The activities on the emergency ditching of aircrafts will make available efficient simulation-based strategies for a goal-oriented optimization and increase of handling- and approach-condition windows that secures a safe ditch. The simulation environment, developed and validated due to the testing activities of CNR, will also provide an improved understanding of physical phenomena enabling an advanced design for reducing weight.

The development of computational models for the prediction of the fuel behavior in the tank and their integration into an industrial design framework will have enormous potential if applied to upgrades of already certified aircraft.

The design of new instruments and enabling technologies for EO in collaboration with the international space agencies, ESA and ASI in particular, and with the main industries is a strong asset of the PA.

Integration and synergistic use of high spatial resolution microwave and optical data allows monitoring and prevention of natural and man-forced disasters (e.g. earthquakes, floods, landslides, oil spills, pollution) providing fundamental information for designing a mitigation risk strategy, an early warning alert or addressing the post-event strategies.

High resolution monitoring of geo-bio physical variables (e.g. agricultural, forest and primary production, soil moisture, snow mass and snow condition) has an economic impact while the information provided at coarse scale (e.g. from microwave radiometers) contribute to the weather prediction and climate studies investigations.

The microwave radiometers CIMR and MWI are under development for global weather forecasting, climate monitoring and cryosphere sciences. MWI will provide data of great accuracy and resolution for ocean temperature and surface wind speed. CIMR aims at sea ice monitoring with very high spatial resolution.

CNR activities on EM and statistical modelling of EO data, impact on many applications. Surface soil moisture is of scientific, applicative and economic interest for water management, food security and agricultural production.

Forward and inverse modelling capabilities play a leading role for atmospheric monitoring and represent the key for further scientific and technological achievements and for new applications and services in view of commercial returns.

The use of HPC infrastructures allows generating fast and efficient EO processing tools and applying innovative instruments for EO data analysis, thus fostering services operated by institutions and industries that can provide value added information to such final users, as public authorities and policy makers.
The use of efficient planning and scheduling AI algorithms for managing EO activities will reduce the delays and improve the quality of the sensed data boosting the mission survival chances, extending mission lifespan and increasing science return.

Ship classification and identification have impacts on the detection of such illegal activities as unauthorized fishing, irregular migration and related smuggling activities.

All activities of design and development of novel methods for data fusion, pattern recognition, supervised and unsupervised classification, multi-temporal analysis of EO data play a key role in the interpretation of complex environmental scenarios.

Advanced methods for automatic analysis of large EO datasets are crucial for natural resource monitoring as well as for detecting warning signals related to natural/man-made disaster.

Grid / Cloud computing and geospatial data infrastructures are becoming more and more important for modeling and processing the huge amounts of EO data.

4. EMERGING RESEARCH CHALLENGES

Research challenges in space activities relate to long term sustainability. Autonomous navigation to in-orbit collision avoidance is gaining importance due the forthcoming large constellations.

Similarly, satellite constellation and formations will provide data with new unprecedented observation and diversity features. The huge amount of EO data opens new perspectives to develop innovative processing methodologies such as information extraction by exploiting artificial intelligence.

In communications, the research challenges are fostering high data rates, high reliability, and a low latency. Novel network architectures aiming at integrating ground, aerial and space networks in the so-called Space-Terrestrial Integrated Network (STIN) need investigation.

Simulation tools for aircraft ditching and fuel sloshing need a further development to improve efficiency and accuracy. Exploiting approximate models is necessary to optimize procedures to design simplified approaches (low fidelity).

5. CONCLUSIONS

The PA is substantial and well established in the framework of aerospace and EO activities at national and international level as witnessed by the large number of its projects and facilities. Projects are scientifically and technologically sound, consistent and sometimes well-funded.

Many researchers are involved in the activities of the PA. Their competences and skills are broad and significant in the fields of space technologies and space safety, space communication and aeronautics, Earth observation Technologies model based data interpretation, ICT tools for the management, processing, representation and exploitation of EO data.

The importance of the scientific programs in which the PA operates is impressive. The scientific scenario for the future appears robust and consistent since several important programs and missions are foreseen in the framework of ESA and ASI initiatives. The role of PA research is often relevant on these programs with the agencies or under contracts funded by the industries operating on the related activities. As a consequence, the procurement of resources for future PA activities appears well based.

The technological impact of the PA on modern society is unquestionable. Issues as satellite technology, for navigation, communications, meteorology and Earth observation are fundamental. It social impact is relevant since its outcomes affect agriculture planning, disaster management, medicine, land monitoring, transportation, many other fields of anthropic interested and could be a valid tool for policy makers.

A final notation concerns the expertise of people involved in the PA. The training phase for researchers involved in space activity is recognize to be long and specific. This aspect should push the maintenance of the expertise in the PA by suitable recruitment policies.
AP13 SECURE SOCIETIES

EXECUTIVE SUMMARY

The challenges related to Secure Societies encompass a large number of technological and scientific fields together with social science, with the final aim to design and implement solutions for safety and security by respecting the privacy of the citizens. Several main thematic areas can be identified according to the societal needs, which are requiring multi-disciplinary approaches and a continuously improved knowledge sharing and exchange among different worlds (practitioners, end-users, scientists, technologists, humanists).

In this context, DIITET is able to give an answer to the present and future technological and scientific challenges in national and international programmes (H2020, FP9, EDA,...), which have an impact on the improvement of the societal resilience.

In particular, the Institutes of DIITET are carrying on state-of-art activities in four areas.

The first one addresses the protection and the improvement of the critical infrastructures and of the Built Environment; in this field, DIITET is able to provide integrated solutions for the cyber-physical security and safety, as well as recommendations and strategies for the planning and designing of the built environment in view of the resilience improvement. Attention is also given to disaster risk management by the adoption of approaches combining modelling and inspection tools.

The second area is concerned with the fight against crime and terrorism, where DIITET has the capability to design and implement solutions for the effective crisis management in the cases of crowded areas and large events and methodologies/technologies for the detection and characterization of dangerous substances and objects. A new thematic is also under development regarding the use of social media as a support to crime prevention.

The third area is concerned with the border and maritime security, which is tackled under a holistic approach based mostly on the integration of novel surveillance technologies from different observation platforms (satellite, airborne, UAV, in-situ) and exploiting the advanced concepts of the robotics.

The last area is concerned with the ethical and social aspects of the security, where the contribution of DIITET addresses two specific necessities: 1) the safety of the workers against electromagnetic risk 2) the privacy issues associated to the surveillance systems.

Of course, this document is also and more important for renewing the knowledge sharing/integration in AP and between this AP and the other ones, in order to identify and give an answer to future scientific and social challenges in the field of safety and security.

1. STATE OF THE ART OF THE RELEVANT SCIENTIFIC AREA

Improvement of the Resilience for Critical infrastructures and Built Environment (including Cultural Heritage)

Cyber-physical security of critical infrastructures

Critical infrastructures are typically cyber-physical systems, often showing strong interconnections such that the disruption/collapse of one leads to a cascading/escalating effects on others (this is, typically, the case of electric power generation blackout). Analysis and assessment of resilience-related indicators of cyber-physical systems providing vital services, to detect vulnerabilities and support system design improvements, are among relevant research activities in this context (ISTI).
The study of innovative and last generation threats (malware, virus, dos tools, trojans, wireless attacks, covert channels, darknet threats) and the design and development of novel protection algorithms and solutions is of increasing interest and covers contexts, such as critical networks, infrastructures and organizations and different scenarios and environments (IEIIT).

**Safety of critical infrastructures and built environment**

In the field of protection of critical infrastructures, the theme of the analysis, prevention and mitigation of the risks associated with chemical processes and accidental combustion phenomena (explosions, fires, and release of toxic substances) is of paramount importance (IRC). Furthermore, it is essential to address detection and monitoring of leakages or unwanted release of CBRNE substances, by using remotely controlled sensors for gases, volatile substances, liquids, or spectroscopic X-ray detectors (IMEM). The above aspects are relevant to the sustainability of the process industry as well as to the effectiveness of both land use planning and civil protection action.

The design and implementation of systems able to couple long-term monitoring and quick damage assessment for critical infrastructures and built environment is another important research theme. The aim is the development of solutions integrating sensing technologies from different observation platforms (satellite, airborne, drones, in-situ) for the multi-scale monitoring and surveillance, not only of the structures but even of the embedding territory. The assimilation of the structural health monitoring results (based on non-destructive techniques) in modeling approaches for structural analysis plays a crucial role in supporting the decisions for long-term maintenance and management. (IREA, IFAC, ISTI, INM).

**Improvement of the resilience for Built Environment and Urban Areas**

Every year, high-impact weather events (HIWE) cause significant damages and casualties. Several research activities aim at supporting and facilitating the study of HIWE in a fully probabilistic multi-model and multi-data virtual research environments. Besides the pure probabilistic modelling of phenomena, other approaches are strongly connected to the three dimensional spatial extent of the entity under investigation and are based on surface or volume analysis and inspection. These approaches have applications in environmental monitoring, hazardous event prediction, structural maintenance, quality control to name a few. Digital Terrain models are ubiquitous in geospatial applications; 3D scalar and vector fields are used to model and simulate the state and evolution of environmental parameters, such as the evolution of the maxima of the rainfall field; computer vision is widely used for structural inspection. (IMATI)

The disaster risk is a crucial factor to be accounted for during the planning and design of built environment in order to improve resilience and assure the safety of the occupants. In this context, it is necessary to change paradigm and turns from the design, on the basis of only historical data, to the one based also on the forecast of future conditions. To pursue this aim, the research efforts are towards new approaches formulating methodologies and tools to evaluate the construction product and improving disaster resilience and risk prevention and management (ITC).

**Fight against crime and terrorism**

**Physical threats detection**

The development of systems able to detect and characterize dangerous substances and targets is now focusing on the design of: advanced X-ray scanners employed for baggage or goods controls in order to identify dangerous or illegal material, where the necessity is to improve their capability to discriminate target materials; systems for the detection of radioactive material in terroristic actions; radar systems for detection of dangerous concealed objects and landmines and IED (IREA, IMEM). Distributed sensing of dangerous
and/or explosive substances is of primary importance and research efforts aim at improving sensitivity, size, cost and power-consumption, mainly to create large networks of stand-alone monitoring units (IMEM).

Crisis management for large events

Crowded areas and large events call for technologies aimed at monitoring, predicting and properly reacting to movements of people masses. It is of paramount importance to develop solutions able to collect and process heterogeneous data so to support risk analysis processes. These processes are based on approaches, which often need to be properly tuned to the target computing infrastructure. A recent trend is to run these algorithms on complex, heterogeneous and distributed platform composed of IoT devices, Clouds and Cloudlets; many contributions have been proposed so far, including novel decentralized interaction paradigms, 5G-based communications as well as software defined infrastructures. (ISTI)

In this scenario, research efforts are also devoted to the design of effective techniques and technologies able to gather and process data from Social Media in near real-time by providing scalable data analytics approaches to support decision in crisis management (IIT).

Social media analysis as support to crime prevention

In the last years, there is an increasing research on the development of tools based on Social media as support to crime prevention by LEAs. In particular, the open issues concern with solutions enabling access to social media data, development of distributed and scalable algorithms (IIT).

Border and maritime security

Maritime/marine wide area surveillance

Synthetic Aperture Radar (SAR) from satellite platforms is one of the most deployed technologies for a wide area surveillance. In particular, a huge research effort has been devoted to target (ship) detection, classification and identification as well as the integration of SAR and optical data and the use of signals received from collaborative (unmanned) vessels as auxiliary information (ISTI, INM). Attention is also devoted to the development of fluorescence LIDAR systems as a useful tool for oil spills characterization (IFAC).

Security on ships and in port areas

It is important to design and implement:
- new on-board systems for security of passengers and crew, based on the integration of multi-sensorial surveillance and monitoring technologies (biometry, computer vision systems, radar,..) supervised by ICT architectures (IREA).
- Systems for security of ports based on the integration of sensing technologies from multi-observational platforms (airborne, drones, on-ground, underwater) for the control of the persons and goods (containers, vehicles,...) (IREA, IMEM, INM).

Robotics and UAV for maritime security

Robotic platforms, under-sea and surface, are important in the exploration of unknown environments, sampling and environmental characterization (bathymetry, measurement of geophysical or biological parameters, tracking in - pollutants, etc.), protection of coastal / port areas, support in intervention operations. The use of robotic units improves the quality of the collected data, in terms of resolution and repeatability of the measurement, as well as an optimization of the sampling times, thus leading to a global saving in terms of economic resources. A further reduction in costs is achieved through teams of autonomous
small-medium sized vehicles characterized by reduced sensory and logistical equipment simplified. Recent studies have led to the development of intelligent robotic systems able to cooperate closely with humans (divers), in order to provide support in critical activities. Maritime surveillance activities also require in-flight observations, which can be supported by autonomous systems (drones), to allow fast surveillance. These systems can be coupled with autonomous marine platforms, thus extending the observational coverage (INM).

**Ethical Societal Dimension and Social Security**

*EMF safety in work environment*

The promulgation of the 2013/35/EU Directive generated a considerable demand, by public and private control bodies, for know-how about the assessment of occupational exposure to electromagnetic field. The publication of the "Non-binding Guide to Good Practices for the Implementation of the Directive" (Nov 2014) did not meet all the needs. At the time of the transposition of the Directive in the Italian law (Aug 2016), resources (specialists, standardized assessment procedures and instrument chains) able to face these issues were not completely available; even the awareness on occupational EMF risks was lacking in many public and private bodies (IFAC).

Furthermore, the issue of occupational exposure to electromagnetic fields has to be addressed by developing tools and strategies for exposure assessment of workers in health (with particular attention to Magnetic Resonance Imaging, MRI, environments) and maritime sectors, and for the evaluation of possible health effects (IREA).

*Privacy issues in Security systems*

The awareness about the respect of the privacy of the people represents one of the main constraint in designing technological solutions. Attention is devoted to the development of privacy aware physical surveillance systems, where the research is focussed on approaches to ease the video control of physical resources (including access to sensitive location) still being able to minimize the data collected/stored and processed (IIT, INM).

2. CONTRIBUTION TO THE RELEVANT SCIENTIFIC AREA

**Improvement of the Resilience for Critical infrastructures and Built Environment (including Cultural Heritage)**

*Cyber-physical security of critical infrastructures*

ISTI carries out analysis and assessment of critical infrastructures through the development of a stochastic model-based framework to analyze the effect of interdependencies in smart grids and to provide quantitative assessment of resilience-related indicators in presence of malfunctions. Quantifying the impact of failures (due to either accidental faults or cyber-attacks) on the capability to provide correct service is a key factor for designing countermeasures to mitigate vulnerabilities revealed in critical assets.

Network Security group of the IEIIT is a pioneer in the design of innovative cyber-attacks, and has brought contribution to the research, by introducing the term “slow dos attack”, relatively to last generation denial of service attacks, also by proving for the first time that such threats can be successfully executed on not performant hosts. Simultaneously, protection methodologies, applied to different last generation cyber-threats, were proposed. IEIIT has implemented advanced algorithms to protect against new generation
attacks and solutions aimed at optimizing the performance of a telecommunications network. The focus is not only in critical infrastructures in general (see ANASTACIA project), but also on specific infrastructures (see FINSEC project).

**Safety of critical infrastructures and built environment**

IRC carries out activities along three main research lines, by adopting approaches based on the development of experimental prototypes and protocols as well as predictive mathematical models, and theoretical and numerical methodologies.

1) Process safety - Loss of control of chemical systems: runaway phenomena; instabilities of chemical processes; industrial toxicology (products of thermal decomposition, and organic and inorganic particulate matter produced by combustion systems);

2) Combustion safety - Explosion phenomena of gas/vapor, dust and hybrid (dust-gas/vapor) systems; propagation and extinguishment of industrial fires; response of materials to fires; propagation of wildland fires on a landscape;

3) Risk assessment - Methodologies for Na-Tech, domino effect and security; land use planning for industrial sites and forest management; methodologies for the analysis of industrial and natural hazards.

IREA has significant expertise in designing and implementing sensing and monitoring solutions based on the integration of sensing technologies. The relevant technologies are: Synthetic Aperture Radar for the monitoring of the displacement (deformations) of the soil and structures by exploiting Sentinel and COSMO-SKYMED data; optic fiber sensor for a distributed monitoring of temperature and strain over long distance (till kilometres) and resolution of the order of meter; ground penetrating radar systems on several platforms (helicopter, UAV, on-ground) for inspection of the underground and inner parts of the structures.

ISTI has consolidated competences about the development of mechanical models and software for the structural analysis and health monitoring of ancient masonry constructions. In particular, the NOSA-ITACA FE code (available at www.nosaitaca.it) allows for modelling the nonlinear behaviour of masonry constructions under static and dynamic loads, by taking into account the material’s inability to withstand tensile stresses.

IFAC gives its contribution with:

1) Design and construction of fluorescence LIDAR systems (spectral and temporal domain, fluorescence hyperspectral imaging, fluorescence lifetime imaging) operating from different platforms (ground-based, airborne, helicopter, shipborne).

2) Design and implementation of ad-hoc algorithms for lidar data processing in specific contexts (cultural heritage, railway infrastructure, etc.).

3) Thermographic analysis with state-of-the art instrumentation and physical-mathematical modelling of thermal processes.

**Improvement of the resilience for built Environment and Urban Areas**

IMATI is involved in research activities to support and facilitate the study of HIWE in a fully probabilistic multi-model and multi-data virtual research environments, through the seamless integration of heterogeneous hydro-meteorological modelling and data services and focusing on the event scale (days to weeks, DRIHM and DRIHM2US EU projects). IMATI works also in the modeling of big geospatial data (e.g., indexing and structuring of LiDAR point clouds for fast access to relevant data, in the context of the iQmulus EU project) and has expertise in the morphological characterization, e.g., for the identification of drainage basin and the terrain change detection in successive campaigns. IMATI adopts change detection techniques on rain fields to track storms and predict hazards. IMATI is also developing methods for the analysis of 3D scalar fields for driving the adaptive sampling of environmental parameters, e.g. for real-time water pollution monitoring (MATRAC Interreg project). IMATI has expertise in point clouds registration and in surface analysis and
characterization for the damage detection of wagons and for the quality evaluation of naval hulls, by using 3D computational geometry approach and not vision methods.

ITC carries out research for code developing and technical assessment of innovative materials and products for construction, through:

1) Approaches able to evaluate the resilience and the impact on the societal security of the new construction products subjected to earthquake, flood, freezing weather, hail, high winds, hurricane, lightning, tornado and wildfire;

2) Teaching the techniques for assessing risk levels and resilience of the installed construction product in courses and training schools for engineers, architects, experts, consultants and manufacturers;

3) Giving technical support to the Community institutions and the Member States towards issuing binding technical standards;

4) Providing society with a sense of security of the new buildings despite the unstable environmental conditions.

**Fight against crime and terrorism**

*Physical threats detection*

IMEM is now developing:

1) on-demand production of room-temperature spectroscopic X-ray and gamma-ray detectors and detection systems to be used in spectroscopic x-ray scanners or compact devices for detection and identification of radioactive sources (also integrated in aerial/terrestrial drones);

2) high sensitivity sensors for gas and volatile substances detection, based on nanostructured oxide materials, on functionalized semiconducting nanowires and carbon nanotubes;

3) sensors for detection of chemical substances in liquids.

IREA has expertise in the development of advanced data processing (microwave imaging) for Through wall imaging, concealed objects detection and landmine/IED detection/localization, also thanks to the adoption of new observation configurations (forward looking, imaging beyond an obstacle) requiring the analysis by means of advanced electromagnetic modelling.

*Crisis management for large events*

ISTI contributes to crisis management in crowded areas and large events with smart and decentralized solutions targeting infrastructures for enabling the distributed data monitoring and collection as well as the timely filtering and analysis of the collected data. ISTI also develops advanced data analytics solutions able to extract useful and contextualized knowledge from data, such as people presence, trajectories characterizing people masses, optimized escape routes. The derived knowledge can be presented and visualized to event organizers or security officers.

IIT is working on the capability to exploit Social Media data with the aim to design and implements situational awareness tools for crisis management in large events. The proposed techniques exploit big data technologies and advanced artificial intelligence algorithms so to extract information supporting crisis management.

*Social media analysis as support to crime prevention*

Social Media analysis is today a critical brick in supporting LEA’s work in crime prevention. IIT is making research efforts to develop tools for: Social Media Analysis for crime prevention (hate speech detection,
analysis of users’ interactions, face similarity recognition, etc.); Social Sensing for Social Good; Health metrics for social ecosystems.

**Border and maritime security**

*Maritime/marine wide area surveillance*

ISTI is involved in maritime surveillance solutions by developing:

i) marine safety/security surveillance and monitoring services;

ii) pervasive smart camera networks for environmental monitoring and video surveillance;

iii) computer vision methods making Unmanned Aerial Vehicles (UAVs) suitable for applications as monitoring of strategic targets and infrastructures, data acquisition in search and rescue operations and multimodal survey and mapping of large areas.

IFAC gives its contribution with:

- Design and construction of fluorescence LIDAR systems operating from different platforms (airborne, helicopter, shipborne, UAV);

- Design and implementation of ad-hoc algorithms for lidar data processing in characterization of oil spills, colored dissolved organic matter, algal blooms, etc..

*Security on ships and in port areas*

IREA is able to develop technological solutions based on radar systems for the remote monitoring of the movement and behavior of the persons (vital signs, indications of suspected behavior) and degree of occupancy of indoor environments. IREA has also expertise in the development of data processing for Terahertz systems for imaging and spectroscopy analysis of dangerous substances.

IRC can contribute with the safety risk assessment for ships and port areas, where flammable substances are stored, handled, and transported.

*Robotics and UAV for maritime security*

INM has expertise in the field of cooperative autonomous robotic systems for both waterborne and airborne segments, able to gather multispectral data in a reduced time-frame, by providing remote sensing to human operators. Measure-based and adaptive decision schemes provide advanced autonomous capabilities allowing the robotic framework to evolve and comply with a time-changing operating environment.

**Ethical Societal Dimension and Social Security**

*EMF safety in work environment*

IFAC can contribute in the field of the assessment of occupational exposure to EMF through: A) management of measurement surveys in workplaces and in the environment; B) teaching in training events for employers, consultants and safety personnel; C) design and development of standardized methods, *ad hoc* instrument chains and adequate measurement and data processing procedures, both for radiometric and dosimetric approaches.

The contributions of IREA to the issue of occupational exposure to EMFs include:

- Measurement campaigns in living and working environments;

- Development of numerical tools for the computation of exposure levels in MRI environments;
- Characterization of EMFs sources and exposure scenarios for workers of the maritime sector;
- Evaluation of genotoxic effects in biological samples of buccal mucosa from exposed workers;
- Education, training and information activities for workers and security managers through the development of websites, videos and the use of augmented reality communication techniques.

Privacy issues in Security systems

IIT, with the support of INM for maritime environment, is able to produce systems that allow a careful control of the situation using surveillance systems. In addition, these systems also can protect the privacy of the involved people, by limiting at minimum the personal identifiable information. The systems work both with biometric aspects as well as for mobility patterns and allows a win-win solutions for security and privacy.

3. IMPACT

Scientific impact

- Number of papers (only on International Journals in the period 2013-to present: about 360
- Organization and participation in scientific committees of main events (conferences, workshops): About 60. (The detailed list is reported as an ANNEX and we are not counting the number of editions for the same conference)
- Editorial Board membership of Journals

Editor in Chief

Open Access Journal HERITAGE (http://www.mdpi.com/journal/heritage)

Members of EBM

IEEE Transactions of Geoscience and Remote Sensing, IEEE Transactions on Computational Imaging, Remote Sensing (MDPI); Heritage (MDPI); IEEE Transactions on Image Processing; Science Publishing Group Communications, 2018; STRUCTURAL MAGAZINE; Computers journal (MDPI); Bioelectromagnetics; Plos One; Scientific Reports; Frontiers in Public Health – Radiation and Health; Scientific World Journal – Biophysics; The Open Biomedical Engineering Journal.

Guest Editors of Special Issues: 23

- Awards
  - Serit (Security Research in ITaly) Award 2012 to the laboratory “Radar for security applications and land monitoring IREA”, whose coordinators are Gianfranco Fornaro and Francesco Soldovieri.
  - Andrea Zappettini: Room Temperature Semiconductor Detector Scientist Award 2017, for lifetime achievement - Atlanta, USA, October 24th 2017 (by Room Temperature Semiconductor Detector Steering Committee)

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• Best Paper Award for the paper "Automatic Aerial Image Alignment for GeoMemories" at MMEDIA 2013, The Fifth International Conferences on Advances in Multimedia, Venice, Italy

• SAGE Ocean Concept Grant 2018 for the project "Digital DNA Toolbox". Sage Publishing.

• "Occupational exposure to electromagnetic fields in MRI: a tool for risk assessment". 2016 Best Italian Electromagnetic Compatibility Poster Prize, at the 2016 IEEE Electromagnetic Compatibility day


- Participation in European Research Infrastructures

ISTI is a member of European Research Infrastructures SoBigData

ITC is member of EOTA, a non-profit organization that coordinates the application of the procedures set out for a request for a European Technical Assessment (ETA) and for the procedure adopting a European Assessment Document (EAD). EOTA also informs the European Commission (EC) and the Standing Committee on Construction of any question related to the preparation of EADs and suggests improvements to the EC based on its experience gained.

IREA is involved in E-RiHS.

Industrial impact

- Main collaborations with companies

IFAC has helped to address non-trivial issues of assessment of exposure to electromagnetic fields in many large Italian companies, such as: Enel, Terna, Trenitalia, Italcertifer, Eni.

IFAC has worked in collaboration with a small enterprise to the feasibility study of an ultra-compact fluorescence LIDAR to be deployed from an Unmanned Air Vehicle (UAV).

IFAC is working in a regional funded project (TOSCA-FI: Optoelectronic tool for mortar-cement-steel structures – Italia railways), in collaboration with SMEs (Tesifer srl, Durazzani srl) and with the support of Trenitalia, for the development of an integrated system for the diagnostics of railway bridges.

CNR (IMATI) leads the Competence Centre START4.0 ”Security and optimization of strategic infrastructures 4.0 “ funded by MISE in Industry 4.0 call. The project involves also the Liguria Region, the Port System Authorities, Unioncamere and the Confindustria Digital Innovation Hub, with the
collaboration of RINA and the participation of Ansaldo Energia, Ansaldo STS, ABB, Cetena, IREN, Leonardo, Softeco and several SMEs.

ISTI collaborates with Mapsat, Telerilevamento Euromediterraneo Srl and Sister Sistemi Territoriali Srl for maritime surveillance in the framework of ESA GSTP project OSIRIS, Optical/SAR data and system Integration for Rush Identification of Ship models.

IMEM cooperates with XNEXT, an Italian SME advanced inspection technology company and CAEN SYS, a SME working on innovative nuclear measurement solutions to enhance Nuclear Safety.

IRC closely collaborates with several companies to address industrial safety issues (Fike Europe BVBA, Mitsubishi Heavy Industries, Avio Aero, DSM S.p.A., Novartis S.p.A., etc.).

ITC supported many national and international manufacturers during the CE process of their construction products.

IREA has an assessed cooperation with several companies as Leonardo, Fincantieri, E-Geos, IDS, NAIS, Consorzio TERN, Digimat, Geocart (not exhaustive list).

- **Involvement in National and International technological platforms**

  SERIT (Security Research in ITaly). SERIT is the Technology Platform on National Security jointly promoted by CNR and Finmeccanica, which groups companies and institutions in Italy dealing with research in the field of Homeland Security. Currently, the platform includes more than 250 Italian partners with over 1000 members. **Fabio Martinelli (IIT) is Co-Chair of SERIT.**

- **Patents**
  - Patent 0001378208, (30 July 2010), Title: Method of processing data collected using Synthetic Aperture Radar (SAR) and its remote sensing system.
  - European Patent (European Patent), EP2017647A1, (Jan 21, 2009). Title: Method for processing data sensed by a synthetic aperture radar (SAR) and related remote sensing system
  - Patent 0001395231, (publication 2009, Grant 2012), Title: System GPR Stepped Frequency reconfigurable.
  - Patent 0001428337 (publication 7/08/2016, Grant 24/04/2017), Title: Georadar System.
  - Patent RM2013A000239 (2013), Title: Apparatus for flammability and explosion tests of uniformly dispersed dusts.

- **Spin-off**
  - SPIN-OFF CNR Remocean SPA (www.remocean.com). The spin-off was founded in 2010 as a partnership between IREA and INSEAN.
  - SPIN-OFF CNR Cleis Security s.r.l. (www.cleissecurity.it). The spin-off was founded in 2006. [https://www.cnr.it/it/spinoff/21/cleis-security-s-r-l](https://www.cnr.it/it/spinoff/21/cleis-security-s-r-l)

**Social Impact**

- **Activities in cooperation with public institutions to address social challenges**
  - IFAC has been collaborating with major national public bodies in charge of physical surveillance of EMF (ISPESL, INAIL, ISS, ENEA, SNPA) with the aim to develop standardized assessment methods.
• The constitution of a joint research center between Polizia di Stato and IIT-CNR (named CRAIM) is currently allowing technology transfer from Social Media research activities to LEA in order to support crime prevention.

• IRC is working in cooperation with ISA (Istituto Superiore Antincendi - Corpo Nazionale dei Vigili del Fuoco), Parco Nazionale del Vesuvio, Regione Campania, and the Greek Ministry of Rural Development and Food (Department of Forest Resources Development) to address the issues of mitigation, prevention and reduction of the risk of forest fire accidents.

• ITC is performing studies and results carried out to support the legislative framework development.

• IREA is Center of Competence of the Civil Protection Department (DPC) for SAR data processing aimed at the detection and evaluation of earth surface deformation. IREA has an assessed cooperation with MIBACT and Archaeological Park of Pompei.

• IREA in the last years, thanks to the collaboration with INAIL-Regione Campania, the issue of occupational exposure to EMFs has been addressed, by developing tools and strategies for exposure assessment of workers in the health (with particular attention to Magnetic Resonance Imaging, MRI, environments) and maritime sectors.

• IMATI is collaborating with REGIONE LIGURIA and ARPAL by providing processing services for the LiDAR data set of Liguria. IMATI has developed new services to provide Regione Liguria for environmental monitoring and protection.

• ISTI is collaborating with many public and private bodies in charge of the maintenance and surveillance of monuments in Tuscany (with particular regard to the territories of Livorno and Lucca). Since 2015 the Laboratory is involved, in collaboration with the Italian Institute of Geophysics and Volcanology (INGV), in the long-term vibration monitoring of medieval towers and bridges. ISTI collaborated with the Florence engineers’ association and the Lucca architects’ association for the organization of training courses.

• INM cooperates with the Italian Navy Hydrographic Institute for deep water Polar environment sampling and formation of young graduate students towards the employment of robotic tools for in-water sampling.

Political impact

- Participation in High-level working groups at national and international level

• Maurizio Aiello is National Representative for Italy at the European Commission, as part of the "Secure Societies - Protecting Freedom and security of Europe and Its Citizens" configuration of the European Research program Horizon 2020.


• Felicita Di Giandomenico is a member of the Connect Advisory Forum for ICT Research and Innovation, European Commission.
- Valeria Di Sarli is Governmental Expert of the CapTech “Ammunition Technologies” in European Defence Agency (EDA) (since 2018), member of the “European Research Community On Flow, Turbulence And Combustion” (ERCOFTAC) (since 2008), and elected member of the directive board of the “Interdivisional Group for Safety in Chemical Environment” (GISAC) of the “Italian Chemical Society” (SCI) (2018-2020).
- Fabio Martinelli is member of the Protection and Security Advisory Group (PASAG) of the EC and First Director of the European Cyber Security Organization.
- Francesco Soldovieri is Governmental Expert of the CapTech “Radio Frequency Sensors Technologies” in European Defence Agency (EDA), member of the Scientific Board of CNIT, Member of the Working Group on the Preparation of the Work Programme 2018-2020 “Secure Societies” (topic Disaster Resilience) for European Commission.
- Maria Rosaria Scarfì is Council member at the Italian Electrotechnical Committee (CEI) (2013-present) and Council member of the European Bioelectromagnetics Association (since 2017). Maria Rosaria Scarfì is a member of the Core group for the preparation of the World Health Organization monograph on risk assessment for RF fields (2012 – present) and of the Scientific Committee of the Swedish Radiation Safety Authority – Electromagnetic Fields (2013-present).
- Olga Zeni and Maria Rosaria Scarfì have been experts of the Working Group on Electromagnetic Fields for the “Opinion on the potential health effects of exposure to electromagnetic fields”, European Commission, Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) (2015).
- Olga Zeni is a member of the the IEEE international committee on Electromagnetic Safety Literature Review (2015 – present).
- ITC is the Italian Technical Assessment Body and develops European Assessment Documents (EADs) used as technical standard in order to affix the EC mark on new and innovative construction products. Moreover, ITC is in charge of the technical assessment of construction products and is entitled to issue European Technical Assessments (ETAs). ITC participates to the Scientific Panel of the CEN/WS Smart-CE-Marking “Smart CE marking for the construction industry”
- ISTI is involved in ITU (United Nations specialized agency for ICT) by participating to the Study Group 13 “Future networks, with focus on IMT-2020, cloud computing and trusted network infrastructures”.

4. EMERGING RESEARCH CHALLENGES

Besides, the “obvious” challenge of the integration of technologies and solutions, which entails a significant effort to activate a bridge between different disciplines, in the following we recall very briefly the specific research challenges.

Modeling of complex systems
Stochastic analysis of critical systems with evolving components (such as distributed energy resources in smart grids); model-based evaluation of large, interconnected systems; trade-offs optimization among contrasting system properties (e.g., safety, availability, security); risk assessment and mitigation.

Cyber-threats and cyber-attacks for critical infrastructures
Integration of Internet of Things devices on critical infrastructures (industrial IoT); Security aspects of Internet of Things devices and networks.

ICT
Big Data Processing Analytics and Social Mining; Management and orchestration of a decentralized computing infrastructure; solutions for achieving distributed indexing and collection of information in emergency scenarios; approaches for the timely and reliable processing of (big) data.
Social media and privacy issues
Privacy aware data analytics, including specific protocols to minimize sensitive and private information for security protocols. This entails both authentication protocols as well as biometric protocols.

Sensing/surveillance technologies: Integration and fusion of multi-scale, multi-depth multi-sensor data; Automatic classification/identification capabilities, with the integration of heterogeneous data; assimilation of the results of monitoring systems in structural analysis methods; new miniaturized sensors; exploitation of new observation platforms.

Safety of critical infrastructures, built environment (including cultural heritage)
Long-term, continuous structural health monitoring and real-time damage detection techniques; development of algorithms for improving efficiency and reliability of numerical codes for structural analysis of the built environment; Safety assessment format for quick aftermath building inspections; Seismic design of selected non-structural building components; innovative materials and products for constructions; New experimental standards/prototypes and new software tools for the design of prevention and mitigation measures for process and combustion safety; development of software tools for the analysis of cascading effects.

Disaster Resilience: safeguarding and securing society
Moving from the event scale to the seasonal scale in the modeling of potentially hazardous events; seamless integration of heterogeneous software tools and data services; new adaptive strategies to environmental sampling in different conditions and deploy fleet of cooperating robotic units; Portable and efficient 3D acquisition for on-field inspection; Augmented Reality vision systems to support human operators in the maintenance of complex structures.

EMF safety in work environment for maritime
EMF exposure conditions of maritime workers by accounting for the features of on-board technologies, sources positions, boats dimensions and materials affecting the EMF propagation.

5. CONCLUSIONS
DIITET institutes can give a significant contribution in many fields of the Secure Societies thematic, as testified by the significant research and technological transfer activities in many areas related to both security and safety. This is testified also by the large number of emerging research challenges envisaged by the contributors to this document, varying from ICT and “software”, hardware solutions as well as modeling tools to critical Infrastructures and Build Environment and maritime safety and security.

A very brief SWOT analysis is summarized in the following.

Strengths: Good scientific impact in terms of scientific production and involvement in the scientific organizations (journals, conferences..); good cooperation with industries and technological transfer activity; good capability to respond to society challenges by the cooperation with public institutions and stakeholders; significant positioning in high-level national and international working groups; significant availability of facilities instrumentations, ICT and modeling tools in several fields; significant involvement in national and international projects (about 4MEuro of funding) also with coordination of H2020 projects; good international visibility.
**Weaknesses:** Despite of the good results obtained by every Institute, the cooperation, collaboration and integrated approach should be encouraged in order to achieve a critical mass and to respond to the scientific and technological challenges.

**Opportunities:** Institutes of AP are able to catch the funding opportunities offered by the different calls, also thanks to the involvement in the high-level working group and the assessed cooperation with different entities (national and international, industries, research institutes, end-users). The transversality is the main characteristic of AP 13 group and this can enable the collaboration with other APs and CNR Departments.

**Threats:** No specific threats are identified, scientific research overlap could be occurred but it could be converted in opportunity of a collaboration among the AP groups, with the aim to tackle emerging challenges and respond to societal needs.
AP14 TECHNOLOGIES FOR SUSTAINABLE AGRICULTURE, FOOD SAFETY AND SECURITY

EXECUTIVE SUMMARY

In the next future agriculture has to answer vital challenges: world population increase, reduction of availability and increase of costs of not renewable resources, and changes in climate, particularly in the Mediterranean area. The foresee climate change will increase the vulnerability of agricultural systems and abiotic/biotic stresses severely constrain yields in crop production. More food, fiber and row material are requested to be produced using natural resources (soil and water) in a more sustainable way, minimizing application of external input such as chemicals (fertilizers, pesticides) and reducing environmental pollution. Sustainable agriculture integrates three main goals: environmental health, economic profitability, and social and economic equity. The digital technologies are recognized as tools to increase agriculture productivity assuring benefits for company, reduce its environmental footprint on not renewable resources and environment, assure healthier and safer food, and guarantee safer work environment and fair revenue for employees. This are the main goals politicians and regulators include in their programs striving for a more economically and ecologically sustainable agriculture. Passive and active sensors, able to collect data at different level at environmental, field, single plant or fruit scale can provide fundamental information for the sustainable management of agriculture crops. Assessment of water available in the soil and status crops at large (regional/continental) and site specific (farm/plant) level support solutions to improve productivity and reduce costs, minimizing environmental impacts. Modern, and even more, future systems for data collection made available large set of information that can be elaborated to predict pests outbreak, illnesses, and stressing conditions for plants and animals affecting the quantity or the quality of the production. More competitive and sustainable agriculture production is possible adopting highly automated processes embedded in more energy efficient and safer vehicles, machinery or processes. Innovative machinery or process are not limited to the production, but include the supply chain and the management of wastes, from agriculture to consumers. Particular attention is payed to the technologies capable of increasing the hygiene and the safety of food, to extend its edibility and maintain and increase the nutritional aspects, and recycling wastes into agricultural production processes.

1. STATE OF THE ART OF THE RELEVANT SCIENTIFIC AREA

The agricultural sector is facing important challenges due to several factors such as increasing worldwide food and feed demand, market globalization and food price volatility, and the needs for more sustainable farming systems in a changing climate scenario. In this framework, technologies can be exploited to contribute to all the value chain of the agro-sector from production to consumption including the overall reduction of waste and its recover. Sensors and GNSS, automation and robotics and other ICT solutions are converging into the so called “smart farming”, which encompasses precision farming (PF) and food safety technologies (handling, preparation, and storage of food). PF is aimed at site specific crop management in order to “produce more with less” by identifying and handling inter and intra-field variability in crops and reducing fertilizer and pesticides application (optimizing the timing, location and quantity). Technologies extend their application also to the post-harvest sector contributing to food quality assessment and to food safety implementation. Finally, innovation is devoted to optimize operator work and to implement healthier and safer working condition by exploiting autonomous or remoted operated machinery. Many of the technologies for “sustainable agriculture and food safety and security” involve disciplines existing and technological innovation developed in DIITET that cover 4 main domain (Figure 1).
Figure 2: The four domains of “TECHNOLOGIES FOR SUSTAINABLE AGRICULTURE AND FOOD SAFETY AND SECURITY”

- Sensors and systems for earth observation and monitoring agro-ecosystem

Sensors and monitoring devices make available high-quality information concerning spatial and temporal variability of crops’ distribution and status to perform large scale (regional/continental) and site specific (farm) monitoring to support solutions focused on improving productivity and reducing costs, while minimizing environmental impacts.

Large scale information can be derived from the integration of high-quality geospatial data (e.g., remotely sensed images, soil and meteorological maps). The recent availability of Sentinel-1 (S-1) and 2 (S-2) systems with their improved spatial/temporal resolution, radiometric accuracy and acquisition plan enables the systematic retrieval of crucial information, such as seasonal crop and soil tillage change maps, time series of Leaf Area Index (LAI), crop biomass and soil moisture content (SM), that are fundamental for improving agricultural monitoring and crop yield forecast.

On the opposite, detailed, in-situ information can be collected by non-destructive and non-invasive sensors acquiring data from proximal distance or directly on plants. Optical sensors are attractive since they can be exploited to record continuous measurements of plant status on the same location. Fluorescence-based sensors are developed to estimate the leaf N content and can be embarked on moving vehicles allowing to cover large areas within relatively short times. In vivo sensors are able to detect in continuous and in real time physiological changes related to stress condition hence are useful to identify in advance dangerous status such as pathogens presence or resource (water, nutrients) shortage.

- Vehicles, robotics and automation

In the last few years, robotics technology has been increasingly employed in agriculture to improve productivity and efficiency of farm machinery. Main objective is to increase the level of driving automation of machinery on farms. Semi or fully automated vehicles, fitted with sensor and connected in real time to the farm data network can lead to save labor time and to perform more efficient farming applications, including regular monitoring of plant growth and precision plant treatments.

GPS-based navigation systems have been in practical use for some years allowing auto-guided agricultural machines but underexploited to, since now, to provide information on the dynamics of the environment and crops status.
Future challenges in machine industry include i) development of smarter vehicles that can operate safely in semi-structured or unstructured dynamic environment ii) the introduction of alternative fossil fuel (LPG, Methane) and electricity as source of energy and electrical actuators and implements. Furthermore advanced perception, and cognitive systems, and human-machine interfaces are required for clear understanding of surrounding world and controls of such enhanced machines. Standards and validation processes have to be developed to assess safety and environmental compliance and performance of such new machines and devices. The interest in such technologies is not limited to the final users, the farms, but it is extended to the sector of manufacturers of agricultural equipment.

- Models, data analysis, and DSS

The large amount of data from sensors made possible to design models able to simulate and forecast the effects of environmental conditions and resources availability (water, nutrients) on crop development, pests outbreak, and final yield, and to adjust operations and chemical applications accordingly.

Soil characteristics, nutrient availability and status of plants are important parameters to make better decisions for an optimized management of crops. Fertilization is one of the agronomic practices that most influences both yield and quality of products, with significantly different responses in relation to the species and cultivar and climate conditions. Moreover, this practice is extremely related to environmental issue in particular in relation to nitrate leaching in water (Directive 91/676/EEC).

The knowledge of the dynamics and the diffusion of a pest is important to define management strategies in areas where pest is already present and/or to tackle the diffusion in new areas. Sustainable pest management is a key component in farming as requested by the European guidelines (Directive 2009/128/EC) that encourage a rational use of pesticides. Decision Support Systems (DSS) developed on pest population dynamics and trophic interaction models describing dynamics in the agro-ecosystems and on crop nutrients and water demands are extremely relevant for a sustainable crop and pests management.

- Food safety and security and environmental protection

Food supply chain faces several challenges to guarantee safe and quality food to meet the growing consumers demand. In food industry different technologies are adopted to contamination and packaging failures control, or identification of items with below standard characteristics. Non-destructive optical tools exist to estimate in situ antioxidants, such as flavonoids and carotenoids allowing for rapid and inexpensive monitoring of compounds in the vegetables. The spectrometric devices can be used when the fruit are still on the plant for fast selection during harvesting, differential storage and processing. A promising technique is the exploitation of low temperature plasmas that has shown anti-microbial capability on food processing in addition to increase seed germination.

Refrigeration are fundamental in the food chain, in terms of safety, keeping temperature of the goods under control to prevent microbial proliferation, and reduction of post-harvest losses. They are however responsible for high environmental footprint, due to energy consumption and GHG direct emissions related to refrigerants, thus, requiring introduction of new gasses and related systems less impacting.

Consumer and regulators are more aware about environmental problems such as soil degradation processes, water overexploitation, decline of biodiversity, carbon emission and pollution from chemicals used in farm processes and organic compound from wastes. Technologies and practices including the post-harvest waste management, are adopted to protect natural resources, reduce impact on environment and increase sustainability of the agricultural system.
2. CONTRIBUTION TO THE RELEVANT SCIENTIFIC AREA

Figure 2 represents schematically the solution developed by research unit of DIITET, the list of specific innovation are reported in Table 1.

Table 1: Synthesis of DIITET competences by sectors

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEN_1</td>
<td>Remote sensing and geo-information for crop and pests monitoring (IREA)</td>
</tr>
<tr>
<td>SEN_2</td>
<td>OECT based in vivo sensors (IMEM)</td>
</tr>
<tr>
<td>SEN_3</td>
<td>Non-destructive fluorescence-based sensors (IFAC)</td>
</tr>
<tr>
<td>SEN_4</td>
<td>Non-destructive optical tools (IFAC)</td>
</tr>
<tr>
<td>SEN_5</td>
<td>Multi-energy scanners (IMEM)</td>
</tr>
<tr>
<td>ROB_1</td>
<td>Ground-based agricultural robots and autonomous vehicles (STIIMA, IMAMOTER)</td>
</tr>
<tr>
<td>MOD_1</td>
<td>Pest Population Dynamics Models and Decision Support Systems (IMATI)</td>
</tr>
<tr>
<td>MOD_2</td>
<td>Soil and water management and conservation in agriculture (IMAMOTER)</td>
</tr>
<tr>
<td>MOD_3</td>
<td>Ergonomics, human factors and safety and health in agriculture (IMAMOTER)</td>
</tr>
<tr>
<td>MOD_4</td>
<td>Data fusion and geo-processing to support Variable Rate application (IREA)</td>
</tr>
<tr>
<td>PRO_1</td>
<td>Refrigerated transport and storage (ITC)</td>
</tr>
</tbody>
</table>
- Sensors and systems for earth observation and monitoring agro-ecosystem

Even though from the technological and instrumental point of view (satellites, drones, sensors, agricultural machinery, software, etc.) development is nowadays very advanced the full exploitation of these solution in real farm condition is the last mile to be addressed.

Satellite sensing technologies are a fundamental input to provide spatio-temporal information about soil condition, crop status and dynamics. Multi-spectral and multi-temporal data from satellite (e.g S-1 & S-2) make possible to i) produce regional scale (e.g. Mediterranean basin) seasonal crop maps by using classification methods, ii) estimate crop fresh biomass, LAI and soil tillage change maps at field scale, and iii) create time series of SM maps with a spatial resolution ranging between 100m and 1000m (See figure 2 Sen_1).

Coping with climate change in agriculture requires the development of frameworks to address food production and security under limiting environmental conditions. A net of smart sensors with different characteristics with specific applications can significantly increase the efficiency of agriculture management and governance, specifically, measurably, and time-bound. Many sensors are nowadays available. Optical sensors based on fluorescence detection can detect the crop/plant physiology status to be translated into plant nutrient and water requirements. The use of non-destructive optical sensors to evaluate in situ plant antioxidants represents a significant innovative tool that can be used on vegetables and fruits to optimize and monitor cultivation practices and postharvest elicitor treatments (See figure 2 Sen_3 and 4). A particularly advanced technique is in vivo sensors, sensors integrated in the plant and able to retrieve directly information on physiological processes, that allows the development of the so call “Internet of Plants”. (See figure 2 Sen_2). Finally, spectroscopic detectors are able to collect at one time several images at several energy bands. CdTe and CdZnTe detectors are the most promising solutions for novel multi-energy x-ray scanners able to assess the quality and status of products in a non-destructive real time (See figure 2 Sen_4).

- Vehicles, robotics and automation

An important aspect of the research deals with the development of smart agricultural vehicles and ground-based robots that, designed or retrofitted with multi-sensor perception systems, are able to accurately monitor the operating environment on a local narrow scale to perform precision farming tasks, such as plant by plant inspection and treatment. In this respect, accurate and robust environmental perception systems is a critical requirement to address unsolved issues including safe interaction with field workers and animals, obstacle detection and situation awareness recognition devoted to increase process automation and safety. Specific objectives of the research in automation dedicated to agricultural machinery and robots are: increased operator safety through multimodal and multichannel sensing; improved persistency under compromised visibility or sensor failure; augmented surround and lateral view for the driver; scene interpretation; obstacle detection; crop assessment and phenotyping (See figure 2 Rob_1) Another important research activity is the development of multi-sensor systems and methods to assess the terrain properties related with the terrain ability to support vehicular motion, to improve vehicle performance and predict the risk of soil compaction by farm machinery.

Self-propelled agricultural vehicles are currently equipped with Diesel engine but, as in other sector of the automotive industry, energies alternative to the liquid fossil fuel are emerging. LPG and methane tractors
are proposed by manufacturers but electricity is on the way as it is the adoption of actuators and implement electrically powered.

Increasing attention is paid to the adoption of user-centered design and ergonomics in agricultural machinery design. It is based on qualitative, quantitative and mixed-methods research to assess performance, safety, comfort and usability in the human-machine/task/environment interaction, considering both physical and cognitive components of the interaction. The discipline requires anthropometric and biomechanical measurements of the individuals and measurements of targeted technical features of the machine to assess the potential physical mismatch between the two components. The process identifies critical issues that may benefit from user-oriented interventions, in terms of both a user-centered (re)design of tasks, machinery and technology, and of targeted information campaigns and training actions, to lead to a better usability and reduction of occupational risks.

- **Models, data analysis, and DSS**

Mathematical models are fundamental to know and forecast the temporal dynamics of many natural phenomena. Pests outbreak and soil management are examples of application of such model in DSS.

Spatial diffusion of pests in a selected area and environmental risk evaluation due to pest invasion are based on the knowledge of the pest dynamics formalized in simulation model. Evaluation of risk and population pressure can be used to take on decisions on the control of the pest to avoid the invasion of an area or to manage the presence of the pest in a crops. In the last case, probabilistic methods can be used to construct a decisional tool able to optimize the chemical application only when needed and not on schedule time taking into account the predicted abundance of the pest on the crop. Software for the decision support system can be developed to assist the farmer supplying useful indications on the time and methods to treat crops with pesticides (See Figure 2 Mod_1 and Mod 3).

Effects of different agricultural management practices including impact of tractors traffic on soil hydrologic characteristics, erosion and soil compaction processes, especially in sloping area can be evaluated by models based on data collected on long term observations.

Calibrated and validated models allows to identify the most correct management solutions in relation to soil mechanical processing, traffic optimization, and planning of farm operations, to improve soil protection, biodiversity conservation and water availability, that are three major ecosystem services that should be provided by agricultural land in addition to crop production (See Figure 2 Mod_2).

UAV are a new innovative flexible solution to acquire Very High Resolution (VHR) data as a support for strategic decision in precision farming application. On the other hand, thanks to the European Copernicus program free of charge, decametric and multi-sensors (Optical multispectral and SAR) satellite data open a new era for the exploitation of Earth Observation imagery in operational workflow devoted to agro monitoring and support for field level agro management. In this context, proper methodological tools are required for a full exploitation of VHR UAV and satellite time series data to extract information and provide that in time for a real user exploitation. Downstream services addressing specific user requirements must be developed exploiting advancement in geo data management by developing algorithm able to extract information from EO data and producing added value decision support products by model assimilation (See Figure 2 Mod_4).

- **Food safety and security and environmental protection**

The electromagnetic technologies for the multi-resolution assessment of product quality within the food-production chain has the unique feature of exploiting the interplay among different portions of the electromagnetic spectrum (microwaves and terahertz). This interplay enables an integrated/simultaneous inspection of foreign bodies, packaging damages, and surface texture and internal properties assessment. (PRO_2) The low temperature plasmas (LTP), generated at atmospheric pressure by different devices, can
directly expose or indirectly put in contact, with water or liquids. LTP technology still requires laboratory studies with multidisciplinary approach for its application on the food chain (PRO_4).

Energy efficiency and reduction environmental impact is a priority for refrigeration systems. The replacement of high GWP fluids with low GWP or natural fluids is one of the priorities. For commercial refrigeration, the market is going towards CO2 as a refrigerant but studies are still needed to improve efficiency and to monitor actual performances. In refrigerated transport, the transition to low GWP or naturals fluids has just started and the gap needs to be rapidly filled. Integration with renewables is also under investigation, tests are approached with numerical and experimental thermos fluid dynamics to study the heat gains and air flow optimization inside the container. The same techniques are applied also to display cabinets and cold rooms. Finally, the control of components and remote monitoring for operation optimization and fault detection is a cross and key topic in refrigeration (PRO_1 and 3).

Wastes for agriculture and agrofood-chain can be submitted to processes for production of fertilizer to be reused in the same sector (circular-economy). This processes requires special procedure to reduce the contribution to GHG emission. This fertilizer can be activated with microorganisms to enhance their nutritional features and biological activity and densified to increase the possibility of storage, transport and distribution when applied with variable rate technology machines. Such fertilizers improve the biodiversity and the carbon content of the soil, and are able to reduce the soil erosion and compaction. Long-term observations are required on fields or large plots to detect soil degradation processes, particularly important in the Mediterranean area where the effects of the climate change jeopardize agriculture production, farmers revenue, and food secure (Pro_5).

3. IMPACT

- **Sensors and systems for earth observation and monitoring agro-ecosystem**

Combining a higher agricultural productivity with the protection of natural ecosystems is one of the key United Nations (UN) Sustainable Development Goals (https://sustainabledevelopment.un.org). It requires the support of Earth Observation systems and of algorithms for a full exploitation of different sensors data (UAV or satellite, multispectral or SAR) to i) provide spatially distributed information on wide area (i.e. crop distribution, crop practices, phenological developments, risk alerts) as a basic component of agriculture monitoring platform (Regional level downstream) and to ii) retrieve crop related information (e.g. biophysical parameters, plant nutritional status, stress condition) in order to generate added value information useful in supporting within field crop management (Local level downstream).

Regional downstream services are fundamental to develop reliable forecast of agricultural production and to create early warning system able to alert on anomalous situations and to support decisions for managing the food security risk. Local downstream services can be exploited directly to support crop management with a direct economic impact for growers and the food industry: farmers can take advantage from the cultivation of well-balanced plants, less susceptible to diseases, reducing the request of chemical application and, consequently labour and pesticides costs hence increasing farming profitability.

In this sector, proximal sensing non-destructive methods can be used to assess nutrients content avoiding destructive sampling and leaf chemical analysis cost. The main impact of such innovation is on the possibility to perform precision fertilization exploiting sensors information and variable rate machineries. According to IOF2020 consortium (https://www.iof2020.eu/trials/arable/precision-crop-management) there is a potential market of 59 million Euro thanks to the expected profitability of about +3% due to increase in nitrogen use efficiency, reduction of water use (-10%) and optimisation of labour (efficiency +5%). Furthermore, the control of the nutrient supply can limit plant diseases and then, indirectly, reduce the use of pesticides contributing to environmental preservation.

The possibility to monitor in vivo and in real time physiological mechanism occurring during plant stress response will reply to the increasing demand of a more sustainable use of resources. Moreover, the
implementation of in vivo sensing technology can also contribute to national and international plant phenotyping infrastructures and networks.

- **Vehicles, robotics and automation**

The development of highly automated vehicles will reduce effort and working hours with positive impact on costs. Vehicle and robots equipped with multi-sensor systems will be able to perceive and understand the surroundings. This will result in an increased safety for people and animals, and will reduce the risk of damages to crops or to machines. Automated agricultural vehicles and ground-based robotic platform will also be able to accurately monitor the operating environment on a local narrow scale to improve precise plant treatments such as precise application of fertilizers or herbicides and plant growth monitoring. In addition, sensing real-time terrain properties the vehicle will be able to adapt to the site-specific environment by varying its velocity or tire pressure, or adjusting the parameters of onboard control and stability systems. The understanding of the role played by different variables related to both the farming system and to the operators (i.e. subjective evaluations, physical and behavioral human variability, and objective characteristics of working conditions and machinery) promotes operators’ health, safety and well-being, and can suggest possible solutions in terms of policies, user-centered (re)design of tasks, machinery and technology, and/or operators’ training, to support and promote a more sustainable agriculture.

Self-propelled vehicles equipped with alternative propulsion system to Diesel engine contribute to the reduction on air pollution in addition to introduce agriculture in network of the smart grid for the use of electrical power.

DIITET structures are accredited as official testing station for safety and performance of agricultural equipment while DIITET representatives participate as expert at national and international level at technical (INAIL) and standardization forum (CUNA, UNI, CEN, ISO, OECD), and supports the manufacturers for the development of new products.

- **Models, data analysis, and DSS**

Mathematical models are useful for many agricultural operations to pass from information to decision. One of those application is for pest population dynamics used to manage the presence of pests by national and international organizations and enterprises. For instance, EFSA uses mathematical models for pest dynamics to promulgate directives for the EU members to control the diffusion of the pest. A mathematical model to describe the dynamics of the grape berry moth has been used in a European project to construct a decision support system for vinegrowers.

- **Food safety and security and environmental protection**

Sensors for food quality and safety should be easy to use, have low impact in the food production chain, be rapid and high-throughput for in-line food monitoring and low-cost. Optical sensors help identifying aspect involved in quality and more profitable products, multi-energy scanners are useful in the field of in-line food safety control, broadband EM diagnostic technology are applicable to the detection of foreign body contaminants in food products along the production chain. An emerging technology in agriculture and food treatment is the low temperature plasma.

In refrigeration technology DIITET representatives assure the Italian presence in the food chain technology projects and supports the national industry, offering scientific collaboration and technology transfer. In transport refrigeration, DIITET representatives acts as expert at national and international level, at political and standardization forum (CTI, CEN, UNECE).

The soil conservation and waste treatments research aims to understand and promote the best agricultural management practices, to optimize the use of natural resources (water and soil), to improve sustainability and performance of the Mediterranean agroecosystems, by promoting solution to make it more resilient to climate uncertainties, also with application of innovative techniques. Regarding soil, considering the climate trend of recent years (changes of rainfall pattern, extreme events causing relevant runoff and soil erosion
processes, and, on the opposite, increasing water scarcity) different management solutions should be selected and evaluated, to preserve essential resources and secure yields under future climate scenario. Concerning wastes technology treatments the densification processes are able to overcome the low density condition of products, recognized as the most important obstacle for transport, handling, storage and application in agriculture.

Many of the scientific workforce belonging to this AP transfer their knowledge in university lecturers, hosting and supervising trainees, thesis and PhD students from the university in their own specific field of study as well as technology transfer initiative are ongoing with well establish collaboration with industry and business service sector.

4. EMERGING RESEARCH CHALLENGES

- **Sensors and systems for earth observation and monitoring agro-ecosystem**
  Data acquisition from sensors (proximal, UAV and satellite), data processing and management to derive crop related information to be included in DSS to create value-added information useful for site specific management by the final operators.

  Development of specific sensors for agricultural and food chain processes such as high energy resolution and high spatial resolution x-ray scanners or OECT based in vivo sensing platform.

- **Vehicles, robotics and automation**
  Advancement in perception systems based on multi-sensor platforms and on the fly processing algorithms integrated on-board agricultural vehicles for highly automated driving and information processing of sensor data in real time field conditions. Users’ acceptability, attitude toward adoption, and ease of use of new technologies.

- **Models, data analysis, and DSS**
  Development of algorithms, models and DSS for pest population dynamics and control, for long term soil degradation prevention, and crop water management to increase resilience and sustainability of agriculture.

- **Food safety and security and environmental protection**
  Development of broadband EM technology for monitoring food quality along the production chain and of LTP for seeds, plants or food treatments.

  Efficiency and environmental improvement, and integration with renewable in refrigeration.

  Investigation on tree and cover crops system and their connections with climatic characteristic and hydrologic response, and livestock waste processing and its application with precision agricultural tools.

5. CONCLUSIONS

Sensing technologies devoted to earth and crop observation are fundamental for agriculture to collect spatio-temporal information about soil condition, water and nutrient availability and demand, crop status and pests dynamics to be fully exploited at different levels to significantly increase the efficiency of use of non-renewable resources and reduce the environmental footprint of agriculture. Significantly innovative tools for agricultural applications are non-destructive sensors based on fluorescence detection for crop and plant physiology. Sensors directly integrated in the plant (in-vivo) are the next challenge in agricultural sensor application. Optical sensors and multi-energy x-ray scanners are promising techniques to assess the fruit and
vegetables nutritional characteristics. Data collected by sensors can be exploited developing algorithms and models for resource management and sustainable chemical application and for pest monitoring and control. Smart agricultural vehicles and ground-based robots, together with drones, are the best platforms to be equipped with sensors for crop and plant observation and inspection and to perform precision farming tasks. These vehicles require accurate and robust environmental perception systems for an effective and safe interaction with the environment and should be able to detect the terrain properties to improve vehicle performance and reduce the risk of soil compaction by farm machinery. Adoption of alternative fuels to the fossil one is the challenge for the future of the agricultural vehicles.

In the food supply chain electromagnetic technologies enables an integrated/simultaneous inspection of properties of product and packaging damages while the low temperature plasmas is a promising technique for food sanitization. Energy efficiency and reduction environmental impact, adopting natural or low GWP fluids and renewable energies all along the food supply chain, are the priority investigation in refrigeration technologies. Intensive land use focusing solely on production results in the decline of agricultural ecosystems, therefore, future agricultural land use should be evaluated considering the trade-offs between food production and the provision of the different ecosystem services. Preserving natural resources from degradation and promoting circular economy paradigm promoting appropriate agricultural system waste management make possible to achieve UN targets for a more sustainable agriculture.
AP15 SUSTAINABLE CONSTRUCTION

EXECUTIVE SUMMARY

The concept of sustainability moves from cultural sediments that are differently dated and that, as a whole, express the synthesis of a social wish and a trend for which Research, in Italy, in Europe and in the world has an important role with the aim to understand the possible applications and to prepare an "intelligent" implementation. The Construction sector seems to be the core of the problem, but also the solution, representing a sector of primary importance in the context of national and European energy and environmental policies and much attention is addressed to this sector.

The activities of the Project Area, hereinafter PA, are related to the national and international context of the construction sector concerning technologies, systems, products and materials, primarily aimed at the improvement of performance levels and safety, as well as the optimization of the final use of energy. The approach, mainly experimental, is developed along two main thematic lines. On the one hand, there is the technological complexity, which concerns materials, components and systems at building scale to the city as a whole. On the other hand, the problems of new construction and those of functional and energy retrofitting of existing building stock and its enhancement are investigated.

These are all technical-scientific objectives with high added value concerning economic and social aspects that are clearly aimed at ensuring the transferability of results in terms of technological innovation. The activities are aimed at the definition of strategies, methods and tools concerning the regeneration of the city and the conscious improvement of integrated energy and environmental and therefore sustainable management of metropolitan areas. Particular attention is addressed to make the performance of buildings measurable in working conditions and in the laboratory.

The approach presents an interesting level of multidisciplinarity and lends itself to contributions of specific scientific competence that DIITET is able to make available internally (e.g. sensors, advanced modelling, ICT, advanced electrical systems, etc.). Training, technical information and transfer of know-how are topics developed across all research and development activities.

The relationship with the academic world and interactions with different national and international research Institutions allows the development of activities in line with current trends.

1. STATE OF THE ART OF THE RELEVANT SCIENTIFIC AREA

Since the oil crises of the 1970’s the scientific community and the worldwide governments have been involved in the debate on thermal and energy performance of buildings attempting to define new strategies for optimization. Despite efforts the subject is still of topical interest. Nowadays buildings in the EU contribute for approximately 40% of energy consumption and 36% of CO₂ emissions. About 75% of the building stock in Europe is energy inefficient and a more extensive renovation of existing buildings has the potential to lead to a reduction of EU’s total energy consumption by 5-6% and a reduction of CO₂ emissions by about 5%. The revision of the 2010/31/EU Energy Performance of Buildings Directive introduces targeted amendments with the aim of accelerating a cost-effective renovation of existing buildings with the vision of a decarbonized building stock by 2050. The revision also supports the deployment of infrastructure for electrical mobility in buildings’ car parks and introduces new provisions to promote the diffusion of smart technologies and technical building systems. The most recent analyses and projections highlight future scenarios in which both total primary energy consumption and CO₂ emissions are set to grow. In particular, the total energy demand is rising from an increasing number of buildings and an increase of global population is expected as well. In this scenario the main challenge is to reduce the energy consumption. For this reason the improvement of energy efficiency of buildings has become a pillar of international energy policies. In particular the overall objective is to enhance energy savings leading to reduced greenhouse gas (GHG) emissions.
emissions and fossil fuel utilization. This aim is pursued by introducing constrains on building requirements in terms of properties of building components (including technological plants) and exploitation of renewable energy sources. In this context the role of nearly zero energy buildings (NZEBs) has established as the standard reference for the target achievements in terms of balance between needs and self-sufficiency for a building under service conditions. As for electrical systems the research effort is centered on both the efficiency improvement of specific components (e.g. power electronic converters, electrical drives, etc.) and on the development of new electrical architectures for power distribution (e.g. DC-based nanogrids), suitably governed by intelligent energy management strategies. A major leap forward in the field of power electronics will be possible by the use of the new wide bandgap semiconductor devices (e.g. SiC, GaN). They have better energy performance with respect to silicon devices and are considered the cornerstone of the development of a new generation of power converter with enhanced efficiency and power density. Furthermore, as for motor drives used in building applications (water pumps, heat pumps, elevators), a viable solution to optimize their operation is the implementation of appropriate minimum-loss control techniques. As a result, a reduction in electricity consumption of users is expected. Similar considerations apply to the exploitation of renewables (e.g., photovoltaics and micro wind energy conversion systems) for supplying the building’s demand; for these systems, the adoption of new maximum power point tracking (MPPT) techniques, taking advantage of Artificial Intelligence, would lead to an increase of self-production and the related cost savings. As for buildings’ electrical architectures, the majority of nanogrid literature is focused on the control and hardware. In order to explore technical issues and to verify the potential returns of nanogrids (especially DC ones), the development and operation of suitable laboratory test prototypes is considered today an essential point. In addition Energy Management Systems (EMSs) have been introduced to perform optimized operations of the electrical grid infrastructure. However the EMSs proposed so far are not conceived to foster their widespread and fast adoption. Several issues are still to be tackled: EMSs should seamlessly integrate with the ecosystem of building devices and appliances; they should interfere as little as possible with the customer’s comfort and habits. Moreover, the energy management algorithms should also allow achieving concurrent advantages for both the end-user and the grid operator. Due to the heterogeneity and the high volume of data involved in building management, big data analysis techniques have to be leveraged to perform a quick and secure access to data that cannot be handled with the traditional approaches of data management. This activity will make predictions available from GSE more efficient, effective and reliable by considering real time energy needs with higher precision. This will improve both offer for the energy market and an accurate purchase strategy for building managers. According to the EU Renewable Heating & Cooling (RHC) platform definition, a hybrid system is “a system combining two or more energy sources to provide heating, cooling and hot water to buildings or industrial processes”. Hybrid concepts represents invaluable opportunity for harnessing the full potential of the EU-renewable energy sources (RES) to cover the heating and cooling demand at building scale with a large potential of energy savings and GHG emissions reduction in the building sector. Today renewable sources can augment existing fossil systems. A new main vision to go beyond is the deployment of a new generation of hybrid systems combining mainly renewable energy sources, thus increasing the RES share. This objective can be pursued by the development of early-design tools, based on LCA and LCC, to be used in the field of refurbishment of buildings towards the NZEB target. A multi-disciplinary approach taking in consideration different variables and aspects usually neglected in practice will be followed. The tools’ databases will also be useful for the development of guidelines for building refurbishment based on models calibrated on a large base of monitored data. In order to face energy efficiency issues, the Distributed Cogeneration can provide a partial solution; anyway their specific and infrastructural costs related to distribution and storage of produced heat are still prohibitive. In order to reduce the negative impact of this last aspect it is possible to reduce the size of these systems by bringing them closer to the final users (microcogeneration); this however leads to an inevitable reduction in electrical efficiency and to an increase of specific costs with significant difficulties in achieving the economic balance point. Moreover the modest electrical efficiency makes it very difficult to match the generation system with the needs of homes in terms of the different thermal to electrical energy ratio. The widespread knowledge of the building stock characteristics is crucial for the development of effective energy policies aimed at reducing energy consumption and GHG emissions. This led over the years to the development of a branch of research with the purpose to identify methods and tools able to characterize the urban fabric from the energy point of view, moving from the assessment of the individual building to the district and the city as a whole.
This change of vision permits to plan targeted operations and to direct the resources to the most significant interventions.

2. CONTRIBUTION TO THE RELEVANT SCIENTIFIC AREA

Starting from available multidisciplinary skills, as well as previous experiences and an availability of medium-large sized equipment, the general objectives of the PA are related to different operational developments that concern a complementarity of the expected results from the different active research groups. The PA deals with the various themes of both advanced sector entrepreneurs and users, developing issues that concern preventive diagnostics, product, process and system optimization, technological and environmental quality, durability, safety, technical suitability for the use of innovative technologies, new experimental processes, correct installation and maintenance, technical information, ... In accordance with the concept of smart and sustainable cities, the topics of Horizon 2020, starting from the monitoring of the territory and the study of new methodological approaches, issues of environmental quality, reduction of energy consumption, etc., technological solutions applicable at building, microurban and urban scale are developed.

At the same time advanced facilities will be developed aimed in particular at assessing the thermal and energy performance of building solutions also with integrated green and at quantifying the maintenance of facade performance under the effect of seismic action.

It is also planned the development of international interest topics related to energy efficiency and smart monitoring of buildings in accordance with the Horizon 2020 objectives, based on decades of experience gained in research groups and enriched by new emerging technologies according to an IoT approach.

The main contributions that the Project Area intends to provide can be summarised as follows:

- Tools and methodologies aimed at: a) assessing sustainability at urban scale; b) designing and verifying buildings correctly from an acoustic point of view; c) managing the processing and dissemination of technical information, including through new training profiles; d) building or retrofitting accessible and assisted environments through the use of home automation solutions integrating technologies and services within the housing ensuring greater safety for the person and the house, comfort, technical organization and communication; e) investigating seismic vulnerability; f) defining procedures for the technical management of post-seismic emergencies and for the management of repair-reconstruction activities; g) developing activities on non-destructive thermal tests aimed at the building and cultural heritage sectors; h) verifying the behaviour of buildings or parts of them under working conditions; i) defining adaptive environmental comfort requirements according to specific classes of users; l) developing new, interconnected, non-invasive and low-cost monitoring devices; m) developing new energy diagnosis tools aimed at reducing the gap between real and calculated behaviour.

- Advanced technological solutions for the optimisation of the energy and environmental performance of the building, evaluating its integration and contribution to the achievement of ZEB objectives, with particular reference to the saving of resources, wellbeing and safety of end users. A building-laboratory will be analysed in its parts (envelope, plant system and systems for the management of energy, water and data flows in order to identify its relations and the possibilities of interaction, to provide a model in which each individual element contributes to achieve the different requirements imposed by the ZEB concept.

- As far as the efficient and reliable use of electricity is concerned, advanced technological solutions will be investigated that will allow intervention at different levels from the single building to the microgrid. Furthermore, with reference to both hardware and software aspects, the following topics will be investigated: optimization of operation electric loads (powered by electronic power converters), testing of new electricity distribution patterns within the building, optimal management of energy flows including storage, use of electricity by buildings’ occupants, e.g. gamification), electrical interaction...
between different buildings and between groups of buildings in the microgrid, supply of ancillary services to the operator of the public electricity grid.

- New infrastructures aimed at: verifying the functional-seismic resistance of facades; characterizing the growing media of green roofs defining standardization and certification procedures for regional, national and international producers; verify the performance of new technological solutions for the efficient and reliable use of electricity in the building; verify the user's engagement with respect to the conscious use of electricity and/or his interaction with automatic energy management systems.

- Construction of a family of mass production ready (TRL 7) micro-generators (named with the acronym of CogIM) from 2 kW to 30 kW of electric power, with the specific aim of integrating synergies of low-cost technologies in order to improve electric and thermal performance, to get higher reliability and reduce sound pressure (<52 dBA). A very high electric efficiency (\(\eta_{el}\) up to 32%) together with a reduced final market price if compared with the state of art (lower than 1000 €/kW of electric power for the bigger plants) permit a very rapid Break Even Point of the investment. The activities considered both the design of very small plants (based on new concept internal combustion engines with a power up to 3 kW) and the transformation of automotive engines in the case of larger plants (up to 30 kW). For small plants innovative schemes characterized by high efficiency despite of a small unit displacement and very low vibration architectures have been proposed. In case of bigger plants, small Heavy-Duty units capable of ensuring high efficiency even in case of severe load factors were obtained, transforming rugged Diesel automotive engines into spark-ignition, natural gas engines (with Ultra Low Emissions). The latter are equipped with high efficient water-cooled asynchronous generators, always designed and assembled at IM together with other elements (heat exchangers, thermal/acoustic cases, etc).

- designing and implementing systems able to manage renewable energy production plants distributed on the national territory. Many buildings are nowadays more and more autonomous and can be viewed as small producers and at the same time consumer of energy. In this respect, within the PA activities it will be really useful the implementation of an innovative system for real-time prediction of the energy needs. It will exploit the latest big data technologies to manage data coming from heterogeneous sources both from a consumer and producer viewpoint. Indeed, the model and the energy source will be decoupled in order to make the system flexible and scalable thus it will be complaint to the requirements for smart cities and intelligent grids.

Due to the heterogeneity and the high volume of data, big data analysis techniques will be leveraged in order to perform a quick and secure access to data that cannot be managed with the traditional approaches of data management.

The following topics are considered:

- **Topic 1: Sustainable Constructions (ITC and ITAE)**
  - Subtopic 1.1: Energy performance certification scheme for existing residential buildings
  - Subtopic 1.2: Definition of methodologies and development of instrumentation aimed at assessing the conditions of indoor Thermohygrometric and Lighting comfort
  - Subtopic 1.3: Definition of an evaluation path for the hydraulic, thermal and energy performance of growing media of green roofs, with the aim of testing laboratory for international guidelines in the UEAtc context
  - Subtopic 1.4: Analysis and characterization of high performance buildings according to Zero Energy Building concept
  - Subtopic 1.5: Environmental retrofit of buildings according to European method “Cost optimal”
  - Subtopic 1.6: Development and characterization of innovative sustainable materials for the acoustic requalification of buildings and urban areas
  - Subtopic 1.7: Definition of special materials for sustainable constructions: development of solution with application of photocatalytic materials
- Subtopic 1.8: Definition of load match and grid interaction indicators in Net Zero Energy Buildings

- **Topic 2: Smart Cities (ITC)**
- Subtopic 2.1: Widespread analysis of buildings energy consumption on a large-scale (district) with “smart metering” method in order to identify the best solutions for urban regeneration
- Subtopic 2.2: Efficient management systems of air conditioning systems at urban scale

- **Topic 3: Advanced Electrical Systems for Sustainable Buildings (INM and ITAE)**
- Subtopic 3.1: Power electronics for building applications
- Subtopic 3.2: Energy efficiency of electrical drives for building applications
- Subtopic 3.3: AC and DC nanogrids/microgrids for building applications
- Subtopic 3.4: Intelligent management of electrical energy in buildings

- **Topic 4: Hybrid systems integrating generation and storage enabling the Smart Building (ITAE and INM)**
- Subtopic 4.1: Electrical storage enabling the Smart Building
- Subtopic 4.2: Advanced thermal storage enabling the Smart Building
- Subtopic 4.3: Development of high-efficiency generators for Smart Building
- Subtopic 4.4: Development of adsorption heat pumps for heating/cooling
- Subtopic 4.5: Development of hybrid system integrating high-efficiency generators and storages (electrical and/or thermal)

- **Topic 5: LCA, ecodesign and carbon footprint of building elements and innovative technologies enabling smart building (ITAE)**
- Subtopic 5.1: LCA, ecodesign and carbon footprint of building elements and innovative technologies enabling smart building
- Subtopic 5.2: Early-design tool, based on LCA and LCC, used in the field of refurbishment of buildings towards the NZEB target in a multi-disciplinary approach

3. IMPACT

The PA’s research results will have direct application in industrial and regulatory fields, both at national and international levels, since active collaborations with the major technical-scientific and research organizations in the construction sector are planned. One of the PA’s activities will be the development of technological solutions for design and construction of ZEB buildings. The major potentials of ZEB buildings are the reduction of energy consumption and environmental pollution, and the possibility to implement design, construction and refurbishment techniques of buildings, according to the interests of public administrations and private property owners in terms of technological innovation and sustainability. Incentive tools and energy efficiency measures are envisaged in this context. The realization of a joint laboratory for testing ZEB buildings will provide a tangible example of energy efficiency measures implementation, thus clarifying the concept of zero energy buildings, still little perceived, in spite of information and dissemination campaigns. Many long-term advantages deriving from the PA’s activities can be envisaged in terms of reduction of the environmental impact of the buildings, operation costs, maintenance costs and costs related to safety and comfort enhancement. The PA aims to promote and implement the smart city paradigm. Furthermore its activities will contribute to trigger a virtuous circle that allows the creation of new markets and services; this could happen starting from the relaunch of investments, creating synergies between research institutes and the business sector. For example, the goal of creating a platform of multi-functional materials complementary to graphene and carbon nanotubes will have a strong impact on the Lombard technological fabric. The activities envisaged by the PA can therefore produce significant effects on the territorial economic development in several aspects: on the one hand the competitiveness of local businesses will increase, benefiting from the possibility of taking advantage of materials testing results and the opportunity to access a database enriched
by the information gathered from the experimental campaign; on the other hand, state-of-the-art laboratories will be solidly integrated into a network of CNR institutes. The properties of the materials developed in the design are enabling to create synergies between research institutes that aim to devise models and innovative systems for reducing the energy consumption of buildings. Within the PA various collaborations are expected, mainly within the laboratory for validation and optimization of the energy-environmental performance of materials, components and casing and plant systems. Furthermore, the PA will respect the objectives of the LE2C cluster, of which ITC, ICMATE, IFN, IMATI, IRSA, ISMAC, ISTM are members. Such CNR Institutes also coordinate operational missions and working groups, providing the opportunity to create contacts with companies operating in the field of energy saving. Lastly, employment growth will be promoted, in which the impact of new high-profile professional figures and of young researchers and technicians, appears to be significant. The PA’s research outcomes in the field of advanced electrical power systems for building applications are expected to be of immediate interest for electrical power system designers, and for industrial manufacturers of renewable generators, power electronics, storage systems and ICT systems. On a wider scale, a widespread adoption of nanogrid/microgrid concept is expected to produce significant social and economic benefits. They derive from the energy efficiency achievements that are inherent in the proposed power system paradigm. Such efficiency is capable of turning into cost reductions for the end-users, but also in a lower carbon footprint of the buildings and in the increase of the medium voltage grid hosting capacity. The latter, in turn, determines less need for further conventional, carbon-based power plants. It is worth considering that the PA’s activities on advanced electrical systems for buildings are located in the general strategy of the expansion of smart grids, which is largely considered a major issue in the architecture of future efficient and reliable power grids. As a matter of fact, such developments are widely supported by central agencies not only of the European Union (e.g. in the programs of Horizon 2020), but also in other countries such as the United States, Japan, China and South Korea.

In particular the research result will provide:

- **Scientific impact**, since they will produce advances in knowledge and skills in the PA sector integrating thermal, electric, economic models and increasingly advanced human behaviors. It will be possible to improve existing legislation and/or to draft new rules; in addition, collaboration between CNR, universities and national and international research institutions will be strengthened. Collaboration between CNR and industrial companies will foster new contracts for industrial research and technology transfer; finally, new laboratories will be built and pilot projects launched for field studies;

- **Social impact**, since the research and dissemination activities aim to raise awareness on both the building users with respect to sustainable purchasing and behavioral choices (reduction of consumption and GHG emissions), and on companies with respect to the compliance of present and future commercial solutions; moreover, the proposed technologies will allow an improved usability of the building by elderly or disabled persons;

- **Economic impact**, as the end user of the building will achieve significant savings while maintaining or increasing comfort levels, and, on the other hand, the impact of buildings on the public electricity grid will be reduced and consequently network operators will be able to implement simpler and more affordable procedures for the grid management; moreover, the number of national consulting and energy management companies (facility management, building management) is expected to increase significantly, with a lower involvement of international companies;

- **Industrial impact**, since the use of the proposed technological solutions implies either the need to design and manufacture new devices (e.g. the EMSs) or to redesign and manufacture existing devices (e.g. more efficient HVAC systems); moreover, the attention to user experience and to the management of significant amounts of data will always be increasing; for the aforementioned reasons, as well as in the civil-construction sector, new opportunities will also be created for companies in the electronic and IT sector;
• Politic impact, with reference to energy use policies (e.g. new pricing schemes, increase in the number of users participating in demand response programs), and to regional and national energy plans (e.g., increase in the share of renewable generation).

4. EMERGING RESEARCH CHALLENGES

The PA is planning to address the emerging challenges of the relevant scientific area by involving in its key activities both high-level, skilled and experienced researchers as well as new recruited young people. Participation in national and international research projects and initiatives with leading research institutions, industries and Universities is considered the main instrument for the achievement of the PA’s goals. Some examples of mainly participations and collaborations of PA Institutes are as follows: European Construction Technology Platform, Cluster Tecnologici Nazionali: Fabbrica Intelligente e Tecnologie per gli Ambienti di Vita, Distretto Produttivo EDA Ecodomus, JP Smart Cities, Energy in Buildings and Communities Programme (EBC) “Energy Flexible Buildings” Annex 67, Distretto ad alta tecnologia per le costruzioni sostenibili, Rete Italiana LCA. National and international collaboration with Institutions, Universities, Ministries and companies

5. CONCLUSIONS

By contributing to about 40% of total final energy consumption and to 36% of CO2 emissions, the construction sector is one of the most important in Europe as regards energy efficiency-related technologies and policies. The sector of buildings is one of the most complex since it encompasses several different crosscutting fields of competence (e.g., engineering, economics, societal sciences, etc.). Moreover, it is closely related to many other strategic sectors such as smart mobility, smart cities, smart appliances, etc.. Today buildings have the potential to gain a central role in the transition of EU citizens from energy consumers to energy prosumers, with growing possibilities of integrating energy savings, energy production and energy storage technologies. For this reasons the energy efficiency achievements in the building sector are widely supported by central agencies both in European Union (e.g. in the programs of Horizon 2020) and in other countries worldwide. On such a basis, thanks to the expertise and the resources of the involved CNR Institutes (ITC, INM, ICAR, ITAE, IM), the PA will provide its contribution to meet current and future scientific and technological challenges in the field of buildings with the aim of enhancing the buildings stock in terms of both energy efficiency and renewable energy production. Specifically the PA will develop the following main topics over the next ten-year time horizon: 1. Sustainable Constructions, 2. Smart Cities, 3. Advanced Electrical Systems for Sustainable Buildings, 4. Electrical storage enabling the Smart Building, 5. LCA, ecodesign and carbon footprint of building elements and innovative technologies enabling smart building. Beneficial impacts of the PA’s work are expected in terms of scientific, societal, economic, industrial and politic outcomes.
**AP 16 SMART CITIES**

**EXECUTIVE SUMMARY**
CNR DIITET AP Smart Cities deals with the sustainability of urban services and improvement of the quality of living of the citizens by collecting data from citizens, places and urban assets, processing and analysing this data to enhance the city services.

At the core of this vision there is the Smart City IoT Platform, a system that enable the collection of data from connected sensors integrated with real-time monitoring systems, crowdsourced personal devices of citizens and various types of everyday objects that are deployed in the city. The information and knowledge that can be acquired from this data is essential to improve city operations and services. Key barriers for the successful deployment of such smart city IoT platform are interoperability, scalability, economic viability, user trust and adoption. HORIZON 2020 Programme identify four main areas:

- Energy, where a first priority is to develop new technologies, approaches and tools to manage and control urban energy systems and grids;
- Transport, where the key priority is to design efficient, safe and sustainable urban mobility systems by reducing the dependence on inefficient private motorized transport while mitigating traffic congestion and other transport-related costs;
- Building, not only to optimise energy consuming, but also, according to the perspective of cognitive building, to offer to people personalized solutions with the aim of improving the quality of life in their living environments, receiving feedbacks and providing recommendations;
- Communities of Citizens, because citizens play a key role in the development of smart cities and represent final users of all the services. Engaging citizen’s means doing everything in an open, inclusive, and participatory way. It also means increasing citizen’s collaboration and participation in smart city governance, with citizens contributing to data collection and the definition, execution and evaluation of smart city programs.

Each of these main topics is briefly discussed in the document and linked to the current activities of CNR research groups in AP SC. The impact, in terms of working groups, joint laboratories, personnel efforts and main projects of the area, is also described. A list of the specific challenges is then presented.

**1. STATE OF THE ART OF THE RELEVANT SCIENTIFIC AREA**
Cities and urban communities in Europe and around the world are undergoing profound socio-economic transformations as a result of global demographic, social and economic trends, as well as technological innovations. The United Nations estimates that 54% of the population lives in urban areas today, but this trend is expected to continue and by 2050 more than 80% of the population will live in cities. Clearly, the speed and scale of urbanization brings huge challenges in terms of resource consumption, transportation needs and economic development. Cities are responsible for more than 75% of a country’s GDP but they also consume about 75 per cent of global primary energy and emit between 50 and 60 per cent of the world’s total greenhouse gases. Urban areas need to manage their development, supporting economic competitiveness, while enhancing social cohesion, environmental sustainability and an increased quality of life of their citizens.

Given the above context, the Horizon 2020 action is promoting a set of initiative to contribute to the “Sustainable Cities and Communities” goal, which is one of the 17 Sustainable Development Goals (SDGs) agreed by the UN member states in 2012. The key challenge is “to significantly increase the overall energy and resource efficiency as well as climate-resilience of Europe’s cities in a holistic fashion, targeting the building stock, energy systems, mobility, climate change, as well as water, air quality, waste and noise”.

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Smart City technologies optimize the sustainability of urban services and improve the quality of living of the citizens by collecting data from citizens, places and urban assets, processing and analysing this data to improve the city services. At the core of this vision there is the **Smart City IoT Platform**, a system that enable the collection of data from connected sensors integrated with real-time monitoring systems, crowdsourced personal devices of citizens and various types of everyday objects that are deployed in the city. The information and knowledge that can be acquired from this data is essential to improve city operations and services. Key barriers for the successful deployment of such smart city IoT platform are interoperability, scalability, economic viability, user trust and adoption. The volume, variety and velocity of the smart city data bring also huge challenges for knowledge discovery and intelligent decision making. Thus, data-related technological innovations, such as big data analytics, edge computing, artificial intelligence and learning approaches are key to cope with the highly dynamic nature of smart cities and learn from real-time data.

In the following we present the key areas of interventions for a Smart City that are identified in the H2020 Programme, and we discuss the open issues.

**Energy**: A first priority is to develop new technologies, approaches and tools to manage and control urban energy systems and grids. Several trends, such as the massive development of renewable energy technologies and distributed generation; the shift towards more electric cooling, heating and transport systems; the key role of energy storage to improve network capacity; the deployment of integrated communication and control systems in the power grid; the active participation of consumers to load balancing in critical situations, are contributing to radically transform the way energy is produced, distributed, and consumed. The goal is to develop integrated approaches to match renewable energy production and consumption at local level enabling community-level microgrids and positive energy districts.

**Transport**: The key priority is to design efficient, safe and sustainable urban mobility systems by reducing the dependence on inefficient private motorized transport while mitigating traffic congestion and other transport-related costs. A combination of factors will contribute to achieve this goal. First of all, information and data communication capabilities will play a key role in the design of next generation traffic management systems supporting new door-to-door mobility services by means of integrated multimodal transport systems. In addition, a new generation of shared mobility services are being designed and seamlessly integrated in the urban mobility landscape to increase the transport efficiency by moving more people in fewer cars. Thus, the design of optimised approaches to foster the growth of real-time ride sharing and promote more sustainable and social-aware travel models are of particular relevance. A third factor that is expected to revolutionize urban mobility, for instance making travel more accessible and safer, is the integration of connected, autonomous and cooperative technologies in the overall transport system. Clearly, cooperation, connectivity, and automation are not only complementary technologies, they reinforce each other and will over time merge completely. Key challenges are to increase the safety of automated vehicles (AVs), allow the coexistence between vehicles with no active control systems and varying levels of automated vehicles, embed shared AVs within the public transportation system, and rethink urban planning accounting for the decline of private cars. Finally, electrification of transport systems will significantly contribute to reduce the impact of transport on the environment and human health. Furthermore, electric vehicles (EVs) will also open the way to innovative uses and services as EVs could play the role of producer-consumers of energy services, through vehicle-to-grid (V2G) and smart charging.

**Building**: A large share of energy in the EU is consumed by buildings (around 40%). Thus, buildings play a key role in the EU sustainability policies and strategic energy plans. All new buildings constructed after 2020 are required to adopt “Nearly Energy Zero Building” (NZEB) standards. Furthermore, buildings are expected to be integrated as active elements of wider energy networks, and to foster innovative mobility solutions. However, building management can go beyond its physical structure, and the monitoring and optimisation of energy performance. A building can contain a variety of sensors and can exploit data retrieved from them to learn the behaviours and daily habits of building inhabitants and users so that it can diagnose and mitigate unwanted events, thus becoming a cognitive building. A cognitive building is able to offer to people, which are geo-spatially tracked, personalized solutions with the aim of improving the quality of life in their living environments, receiving feedbacks and providing recommendations.
Communities of citizens: Citizens play a key role in the development of smart cities. Engaging citizens means doing everything in an open, inclusive, and participatory way. It also means increasing citizens’ collaboration and participation in smart city governance, with citizens contributing to data collection and the definition, execution and evaluation of smart city programs. Clearly, Internet technologies will have a radical effect on cities’ organization and relationship with their citizens by changing the way productive processes are organized, how economic transactions take place, and even how citizens consume culture and leisure service for instance. In addition, online and mobile social networking (MSN) services will be fundamental tools to empower the citizens. Finally, to increase the resilience of urban communities to disasters, the concept of smart city should be embedded within a broader framework of resilient city. For instance, technologies and capabilities for first responders for emergency operations in crisis and disaster situations are needed. Furthermore, cybersecurity should be improved substantially, to ensure the protection of the huge number of IoT devices that will be deployed in the city.

2. CONTRIBUTION TO THE RELEVANT SCIENTIFIC AREA

In the “MOBILITY” thematic area the research lines that are currently active can be grouped as follows:

- **Design of Demand Responsive Transportation (DRT) systems**: One focus is to develop optimised tools for the DRT operational planning, based on Dial-a-Ride models, both for the booking and travel phase of the service. Moreover, innovative algorithms have been studied to support car-sharing systems, bike-sharing and car-pooling in urban and extra-urban context. This activity is also dedicated to the development of new models and tools to promote multimodality and the integration of DRT systems with conventional modes of transport. Involved Institutes: IAC, IASI, IIT

- **Mobility models**: We have developed forecasting models of traffic flows on large-scale road networks by combining integrating fluid-dynamic macroscopic models with cross-over dynamics models, which allows simulating in real-time the traffic status. We also have developed new methodologies for providing real-time information about mobility-related phenomena, e.g. mobility demand models, individual mobility patterns from various mobility-related data sources, including mobile phone data, geo-located media on social networks. These data provide useful real-time insights for transport users and traffic operators, and can help to tackle a vast variety of mobility situations, i.e., congestion, safety, tolling, navigation support. Involved Institutes: IAC, ISTI.

- **Optimisation methods for logistic and transportation service. Logistics and fleet management**: We have developed advanced optimisation methods and tools for planning and real-time operation of smart city logistics and transportation services. We focused on: i) distribution of goods and the management of fleets at different territorial scales, ii) vehicle routing and orienteering problems, and iii) door-to-door waste collection. Involved Institutes: IAC, IASI

- **Virtual Traffic Lights**: This activity focuses on the development of a cooperative and autonomous system for the management of road intersections to reduce traffic congestion and improve road safety. Involved Institutes: IEIIT.

- **Communication systems for vehicular environments**: Our focus is to investigate the hybrid cooperation of different wireless access technologies for ultra-reliable and low-latency communications for connected and autonomous vehicles. In particular, we have developed models and algorithms of D2D communications supporting automotive services. Another aspect is the optimization of V2X communications for rural environments characterized by low vehicle density and natural obstacles. Involved Institutes: IEIIT, IIT, ITAE.

- **Intelligent Transportation Systems**: We have designed platforms and tools for efficient traffic management. One focus is on how to integrate geo-referenced data in the context of smart and sustainable mobility, dealing with data interoperability and standards, crowdsourcing, data visualization and analysis. Another fundamental aspect is to design solutions to reduce emissions and optimize journey times. Furthermore, we have developed smart cameras with cooperative sensing functionalities for real-time and capillary traffic monitoring. Involved Institutes: IMATI, ITAE, ISTI.
In the “ENERGY” thematic area the research lines that are currently active can be grouped as follows:

- **Low-emission vehicles**: The activities are focused on the development of long-range hydrogen vehicles equipped with fuel cells and batteries. Involved Institutes: **ITAE**.

- **Electrical mobility**: We have developed short to mid-term models of electric mobility diffusion to assess the relative infrastructure requirements, to design management tools for smart charging infrastructures, and to evaluate the impact on renewable energy production/storage systems. Involved Institutes: **ITAE, IM, IIT**.

In the “PLATFORMS” thematic area the research lines that are currently active can be grouped as follows:

- **Vehicle-to-Grid (V2G) services**: We have developed optimisation methods for energy management of vehicle battery packs to support smart micro-grids through V2G services, through vehicle to grid services. Another aspect is the development of multi-agent aggregation schemes for private vehicles and public/corporate fleets, leveraging the knowledge of users’ charging behaviours. Involved Institutes: **IM, ITAE**.

- **Power-to-Gas (P2G) systems**: We have developed P2G systems using electrolysis and CO2 recovery for storage or methane network integration. Involved Institutes: **ITAE**.

- **Resiliency in SGs**: We have developed methodologies and tools to increase the resiliency of smart grids against both cyberattacks and faults. Involved Institutes: **IEIIT**.

- **Communication and control of SGs**: We have developed technologies and system to enable distributed communication, measurement and control capabilities within nest-generation power grids. Our focus is on design of: i) reliable, scalable and interoperable communication systems and networks for SGs, using both wireless and PLC technologies; ii) new cooperative or hierarchical methodologies for reliable estimate of SG state; iii) new smart meters; iv) IED technologies for remote management of distributed generators and storage systems; and v) new polyhedral formulations for the problem of the Unit Commitment for thermal power plants. Involved Institutes: **IEIIT, INM, IASI**.

In the “PLATFORAMs” thematic area the research lines that are currently active can be grouped as follows:

- **Smart IoT platforms**: We have developed a Swarm-Edge IoT platform that allows dynamic addition of processors/devices for uninterrupted distributed processing, connectivity and protocol-agnostic heterogeneous by means of using proactive, self-emergent dynamic configurable, software-defined autonomous agents that learn and share data at the edge of the network. The architecture uses Swarm Intelligence (SI) techniques to enable multi-agent artificial intelligence, facilitated collective machine learning, and to provide an AI-based decentralized self-forming intelligence at a high scale. Finally, the SioT paradigm has been integrated to realize a social network of objects. Involved Institutes: **ICAR**.

- **Urban monitoring**: This research activity concerns with the development of sensing technologies, tools, and models for monitoring urban phenomena and knowledge discovery from urban data collected locally. Several aspects are addressed. We have developed reliable, low-cost sensors for obtaining data about weather dynamics, noise levels, atmospheric pollution, environmental indicators, etc. We have also developed sensing technologies for activity recognition and behavioural assessment. Another focus is the development of intelligent cameras for objects and people identification with the use of artificial intelligence technologies based on deep learning. Integration of drone technology and cameras is also investigated. Furthermore, we design new methodologies and service for spatiotemporal monitoring of urban areas by processing remote sensing images, and generating semantic meaningful information, such as flooded areas, burned areas, displacement maps. Finally, we have developed models of the spatiotemporal dynamics of the demands for mobile services in urban areas, as well as land use detection and population density estimation techniques, by leveraging mobile network metadata. Involved Institutes: **ICAR, IEIIT, INAMOTER, IMEM, IRC, ISTI**.
In the “BUILDING” thematic area the research lines that are currently active can be grouped as follows:

- **Building monitoring and control**: Our focus is to design services that make the building intelligent by acting on parameters such as lighting, thermal comfort, air quality, physical safety, etc. We develop sensor networks that are able to monitor both the energy consumption of building environments and users, as well as various environmental parameters (temperature, humidity, air quality, etc.). Moreover, smart cameras can produce images and video to detect danger situations (thefts, aggressions, etc.). The collected data, crossed with each other through appropriate algorithms, allow the development of virtual sensors (intrusion, climatic well-being, energy saving, etc.), and services that assist users in tuning their habits (i) for reducing power consumption; (ii) for safety and comfort issues. Involved Institutes: **ITAE, ISTI, ICAR, ITC.**

- **NZEB technologies**: One focus is the development of standardized panels for ventilated façades or roofs combining PV, solar thermal, insulation, PCM and batteries. The general objective is to innovate the building process considering the advantages associated with using renewable energy generation, storage and energy management in façade. The second focus is the development of hybrid thermal/electric storage based on PCM and batteries, and integrated with renewable energy sources in order to increase the overall energy efficiency of air conditioning systems for residential application. Involved Institutes: **ITAE.**

- **Cognitive buildings**: The goal of the research is to combine IoT technology, cognitive computing, big data, machine learning and reasoning to help people live and work better in buildings, as well as maintain and manage the building itself by providing it with the capabilities to learn over time how to improve building management. Involved Institutes: **ICAR.**

In the “COMMUNITIES OF CITIZENS” thematic area the research lines that are currently active can be grouped as follows:

- **Open Data, Linked Data and semantic technologies**: We have developed methodologies for data publication as Open Data and data integration as Linked Data for e-Government applications. Involved Institutes: **IMATI.**

- **Social networking applications**: One focus is to develop applications and tools for connecting citizens with the social context in which they live to strengthen their links with their neighbourhood thus enabling the volunteering for neighbourhood welfare services. We also design social networking applications to facilitate human interactions and to enable users to share data within temporary and localised social communities based on common interests. Involved Institutes: **IREA, IIT.**

- **Applications for tourism and use of cultural heritage**: We have developed web-based services and mobile apps for facilitating users to plan their visit tours, but also to get detailed and contextualised information about the cultural contents of tourist sites, while they are visiting them. Another activity concerns the design of optimized models for the creation of car sharing and bike-sharing systems for tourism or to choose the optimal pedestrian route. Involved Institutes: **IAC, ISTI.**

- **Applications for a safer and more accessible city**: We have developed algorithms for the optimal management of rescue vehicles in emergency situations. We have also developed models of crowd dynamics and methods for the management of pedestrian flows. Involved Institutes: **IAC.**

- **Water management system**: We have developed a smart system for real-time detection of the saturation of the urban drainage network, the overloading of the sewage treatment plants, and to regulate the flow and water flow in the pipeline. Involved Institutes: **ICAR.**

### 3. IMPACT

DIITET Institutes are participating to several working groups and research alliances, both at the European and Italian level, where emerging research challenges, solutions, strategies and policies relevant to the Smart City domain are discussed. The most relevant are the following:
• European Energy Research Alliance – EERA, with special focus on the Joint Programmes Smart Cities, Energy Storage, and Smart Grid (ITAE)
• Distretto Tecnologico Nazionale sull’Energia – Di.T.N.E. (ITAE)
• Distretto Tecnologico Nazionale sulle Tecnologie Ambienti di Vita – TAV (ICAR)
• Associazione Nazionale per la Telematica per i Trasporti e la Sicurezza – TTS (ITAE)
• Mobilità Idrogeno Italia – MH2IT (ITAE)
• Cluster Tecnologici Nazionali
  o Energia (ITAE)
  o Trasporti (ITAE, IIT, IEIIT)
    ▪ Coordinator of the “Intelligent Transportation System” Woking Group – ITS (IAC)
  o Smart Cities (ITAE)
• European Innovation Partnership on Smart Cities and Community – EIP-SCC (ITC)
• Cluster “smart cities and communities” – Regione Lombardia (IREA)
• Cluster “aerospazio” – Regione Lombardia (IREA)
• Tuscan Rail Technological District – DITECFER (ISTI)

Joint laboratories have been established with universities and public authorities, such as:
• “Intelligent Transportation Systems” Lab, between INM and the Department of Mechanical, Energy, Management and Transportation Engineering (DIME) of the University of Genova.
• “Smart Distributed and Pervasive Systems” – (SPEEDY LAB), ICAR in collaboration with the Department of Mechanical, Energy and Management (DIMEG) of the University of Calabria
• Measurement and Communication for Smart Grids” Lab, between INM and the Department of Energy, Information Engineering and Mathematical Models (DEIM) of the University of Palermo
• “Centro di Ricerca per l’Analisi delle Informazioni Multimediali” – CRAIM, IIT and ISTI in collaboration with Department of Public Safety, Ministry of Internal Affairs
• “European Laboratory on Big Data Analytics and Social Mining” – SoBigData.it Lab, between ISTI, IIT and the Department of Computer Science, University of Pisa

4. EMERGING RESEARCH CHALLENGES

For the above thematic areas, a (incomplete) list of emerging research challenges:
- Integration of thermal storage and hybrid storage with electrical batteries in building management.
- Development of building integrated photovoltaic technologies
- Improve autonomy of hybrid electric vehicles, low-carbon hydrogen including fuel cells
- Connected, cooperative and automated mobility systems
- Data and video analytics for security applications in city environments
- Enabling cognitive smart cities using big data analytics, machine learning and artificial intelligence
- Technologies and tools for positive energy districts and zero-emission mobility and logistics
- Better management of responsive transport systems, fleets and logistic services
- Traffic forecasting models.
- Algorithms and applications for tourism and the use of cultural heritage.
- Identification and use of appropriate data analytics platforms that allow both historical data analysis and predictive analysis.
- Security applications by computer vision methods, such as i) automatic monitoring of strategic targets and infrastructures, ii) real time data acquisition for remote surveillance iii) multimodal survey and mapping of urban areas
5. CONCLUSIONS

Even if there is no single generally acceptable definition for the concept of Smart Cities, it is emerging worldwide a prototype of an urban environment provided with a new generation of innovative services for transportation, energy distribution, environmental monitoring, emergency response, and social activities, which frequently interact with each other thanks to ICT solutions. These networks of relationships lead smart cities to become a system-of-systems, with global missions. This multidimensional and multidisciplinary nature of the Smart City concept implies and requires at level of CNR a strong synergy and a partial overlapping of the current activities with other APs’ such as Future Internet, Healthcare and well-being, Sustainable buildings, Society security. The main difference with each of them is represented by the highly integrated approach which is required in this sector, where each aspect is strictly connected to the others. The 18 CNR Institutes, which work and/or have showed interest in this AP, cover the main areas of activity, and exactly Mobility, Energy, platforms, Buildings and Communities of Citizens. The fields of activity cover:

- participation in several working groups, both at the European and Italian level, in order to discuss emerging research challenges, solutions, strategies and policies;
- joint laboratories with universities and public authorities, as a tangible example of integrated and integrated approach to the problem;
- participation in several national and international projects (only the most relevant in term of funding are listed in the IMPACT section), in order to study and realize a number of solutions to specific problems.
AP17 LOW EMISSION ENERGY TECHNOLOGIES

EXECUTIVE SUMMARY

The current Italian and European policy on energy suggests to re-position research activities on power generation within the context of a renewable energy future.

Europe is benefitting from a rapid increase of renewable power resulting in a severe change in the energy mix. However, the main renewable energy resources (wind, solar, tidal power) are inherently intermittent and non-programmable: their production can be insufficient and asynchronous with demand, thus generating great problems to the grid stability.

In the mid-term, in order to secure the energy supply, conventional power plants, designed for steady full load operation, will be used intermittently to balance the grid. This means that the research activities on fossil fuels will aim to emission control and CO₂ capture processes both effective and economically under intermittent operation mode.

Another important research topic will be the development of energy storage alternatives: fuel cells and chemical energy vectors are investigated within this context.

The future of research in the field of energy technologies for the longer term is most likely in an integrated approach to power, thermal, chemical and materials production, an effort that requires combining expertise in combustion, chemical engineering, mechanical engineering, chemistry, materials science, biotechnology, IT, geology, social science, and economics. In the long-term, the digitization (i.e., the utilization of sensors, big data approaches, automation and artificial intelligence, cybersecurity, etc.) will be another fundamental aspect of the energy production as a consequence of the fourth industrial revolution, similarly to the other industrial processes.

Within this frame, the Department, with its broad spectrum of activities and expertise, is the ideal “environment” to carry out interdisciplinary projects at national and international level. All these aspects are discussed in the document.

1. STATE OF THE ART OF THE RELEVANT SCIENTIFIC AREA

The scenario designed by the SET-Plan

The EU has the ambition to become the world number one in renewable energy. To meet this goal, the EU must lead the development of the next generation of renewable energy technologies. A key aim of the Energy Union is also to increase the number of citizens as active players in a decentralised and digitalised energy system – with a direct role in a cleaner energy production and adjusting their consumption patterns to market signals. Buildings, districts and cities will also need to become smarter to reach ‘zero energy’ levels. The overall goal is to have a more flexible and highly-efficient energy system that incorporates storage capabilities, is better integrated with local heating and cooling networks and that puts consumers at the centre. These challenges call for innovative R&I solutions as the SET Plan sets out to achieve.

Photovoltaic solar energy (PV)

All major future energy scenarios forecast a key role for photovoltaic solar energy. PV currently covers approximately 3% of total EU electricity demand and 2% of the global demand. The PV industry has changed dramatically over the last few years. Italy can play a crucial role in this effort as it hosts 3Sun, the largest European manufacturing industry covering the crucial upstream segments apart from Si feedstock production. Italy identified two major flagship activities (Flagship 1: BIPV; Flagship 2: Utility Scale PV) and is looking to launch a national network of R&I labs in order to maximise the effects of the technology-transfer projects and contribute to the “N.1 in renewables” objective of the SET Plan.
Concentrated Solar Power (CSP)

Coupled with thermal energy storage, CSP can make a significant contribution to the transformation of the European energy system by providing an important share of dispatchable renewable electricity. CSP can facilitate the integration of variable output renewables such as PV or wind energy, thereby contributing to the reliability of the transmission grid. CSP could account for up to 11% of the electricity generated worldwide and up to 4% of the electricity generated in Europe by 2050. The agreed Strategic Targets on CSP concern a significant cost reduction (>40% by 2020) and the development of the next generation of CSP/STE technology (introduction of new cycles including supercritical ones).

Off-shore Wind

Wind energy is expected to provide the largest contribution to the RE targets for 2020 and beyond. By 2020 total installed wind energy capacity could reach 210 GW (14% of electricity demand), and by 2030 it could reach 350 GW (i.e. supplying between 21% and 24% of demand). In order to maintain European leadership, the competitiveness of the offshore wind energy sector must increase further. Two key issues need to be tackled: the reduction of the offshore wind costs through the increase of performance and reliability and the need to develop (floating) substructures or integrated floating wind energy systems for deeper waters and wind energy systems for use in other marine climatic conditions.

Biofuels

In the EU, agricultural biomass is the main feedstock for biofuels. However, the request of renewable biofuel production avoiding competition with food resources, stimulate technologies and research in the direction of second and third biofuels generation (including biofuel production from algae and hydrogen produced from biomass). Biofuels are expected to make a significant contribution in passenger car and urban transport markets as of 2030. New technology developments, such as hydrogenation, could help to match the predicted growth in demand for bio-diesel by diversifying the feedstock used as raw material. Biogas, or ‘green’ natural gas, could see increased use in the transport sector in the future. The production of high quality biogas is one of the most stimulating challenges of the next future.

CCS and CCU

CCS is one of the key promising technologies that can reduce CO₂ emissions in the power generation sector and the only pathway for very stringent GHG emission reductions from specific energy and/or carbon intensive industries that generate CO₂ as part of their production processes. In order to achieve the greenhouse gas emission reductions agreed at COP21 in Paris, CCS will need to be deployed as soon as possible. In order to realise its potential, CCS needs to become a cost-competitive technology and gain public acceptance (mainly regarding storage safety), so that it could start to be commercially deployed and thus contribute to the low-carbon transition of the European economy.

Ocean Energy

Ocean energy is abundant, geographically diverse and renewable. It could meet 10% of the European Union’s power demand by 2050. Ocean energy comprises five distinct technologies: wave energy, tidal stream energy, tidal range energy, ocean energy thermal conversion (OTEC) and salinity gradient power generation. In order to speed up the time to market of ocean energy technologies it is important to prioritise and concentrate efforts for a limited number of technologies. Priority will be given to tidal stream and wave energy, which have a high market potential for Europe and sufficient scale on a European level. It should be noted that OTEC and other technologies could form part of future considerations.

E-Storage

The Implementation Plan of the SET Plan comes at a crucial moment for European Industry. Its scope is batteries for e-mobility and stationary energy storage applications. It is imperative that European industry masters the development, manufacturing, application and recycling of advanced batteries to become competitive in the global battery sector. The Implementation Plan has identified five Flagship R&I initiatives: Materials Flagship; Manufacturing flagship; Fast-charge flagship; Second-use flagship; Recycling flagship).
Resilient and secure European energy system

The goals of the SET-Plan are the development and operation of energy systems showing an appropriate level of resilience, reliability, energy and economic efficiency, leveraging the use and integration of bulk and local resources, with special reference to integrating variable renewables. The variability of renewables, the stochastic nature of loads, the necessity to integrate different energy vectors according to different energy scenarios raise the necessity to develop a strong flexibility. This requires innovative technologies enhancing customer participation, storage, connections between electricity grids and other networks (gas, heat and cold, transport), optimising the use of flexible sustainable combined power and heat generation and the centralization/decentralization of thermal power generation.

Cross cutting heating and cooling technologies for buildings

The total EU28 energy demand for heating and cooling (H/C) equals 51% of the total final energy. With the exception of biomass (12%), the use of renewables for H/C is marginal. The use of renewable energy sources for heating and cooling, such as biomass, solar thermal, geothermal hydrothermal and aerothermal offer a safe, reliable and increasingly cost-competitive solution to all heating and cooling needs. Small and large scale Heat Pumps, District Heating and Cooling (DHC), Micro CHP/CCHP and Thermal Energy Storage (TES) all fit the above definition very well, can be used in buildings, and represent the technology focus of this action.

2. CONTRIBUTION TO THE RELEVANT SCIENTIFIC AREA

1: RENEWABLE ENERGY

Wind energy

Research activities concern floating offshore wind turbines for deep-sea applications as regards platform/turbine integration. Offshore and onshore turbines are investigated by means of aerodynamic and aeroelastic modeling in order to predict aeroloads (wind shear, yaw misalignment, floater motion), response and hub loads. Integration with hydroelastic solvers and control tools is used for preliminary design. Wind turbines noise is predicted by the Acoustic Analogy formulation coupled with suitable CFD aerodynamic solvers, assessing the effect of blades elasticity on the radiated noise.

Ocean Energy

Hydrokinetic turbines for the conversion of ocean and tidal currents represent the most mature technology in the marine renewables sector, while great interest is given to Oscillating Water Column (OWC) as a cost-effective technology to harvest wave energy from coastal infrastructures. Conditions relevant for operation at sea are addressed through computational modeling and tests on lab-scale models. Research addresses the effects of onset flow turbulence, wave/current interactions, seabed flow confinement in shallow waters, interactions among devices in arrays, PTO control strategies, device response to extreme conditions.

Solar energy

A novel concept of indirectly irradiated solar receiver for CHP generation consisting of a compartmented dense gas fluidized bed has been proved. This configuration permits higher operating temperatures, more efficient thermodynamic cycles, endothermic thermochemical reversible reactions for energy storage. A new approach for photoelectrochemical splitting of water into H2 and O2 is investigated with metal oxide electrodes. High efficiency tandem solar cells resulting from the combinations of the Silicon-heterojunction technology are investigated.
2. FLEXIBILITY AND SUSTAINABILITY OF ENERGY AND POWER

Revamping of conventional plants

Scientific topics under investigation regard the behavior of burners and boilers upon dynamic operation modes (switch from oxygen lean to oxygen rich conditions, fuel switch, cold start). Activities address also the conversion of fossil fuels plants into reactors for gas and fuel synthesis.

Emission control

The research concerns the formation of pollutants, in situ, on-line and off line advanced diagnostics of pollutants and ultrafine particles; flame instabilities; Ox, SCR; NOx and particulate reduction; sea water scrubbing with NH3-SCR for marine application; NOx storage-decomposition for automotive application; PM reduction through water vapor condensation; Hg capture from flue gases; purification of CO2 streams; tar and VOC abatement.

Energy storage and carriers

Research addresses electrochemical storage for stationary and transportation applications by means of state-of-the-art batteries, highly reversible and low-cost materials for high battery performances. Energy storage of renewable energy is achieved producing H2 for fuel cells by water photo-electrolysis, by CO2-H2 co-electrolysis, by solar thermochemical splitting of water and CO2. Application of ammonia, a no-carbon energy carrier, to mild combustion is also investigated.

Fuel cells

Activities aim to develop new materials and improved membrane electrode assemblies to reduce costs and increase performance and lifetime. High temperature solid oxide fuel cells are developed for direct feed of biofuels (no intermediate reforming step) and to improve the tolerance to redox and thermal cycles. In the transition period, solid oxide fuel cells can operate efficiently with natural gas.

Integrated Systems

Integrated paths (e.g., fossil+renewables, etc.) are explored to overcome the inherent limitations of renewable energy sources and reduce the cost of energy. Co-combustion of fossil and fuels from wastes is adopted to reduce the CO2 emissions. A new approach couples thermochemical conversion processes with Solar or Wind Power (CSP). Fluidized bed CSP is integrated with thermochemical conversion of biomass to obtain a micro-CHP generator. CSP and wind or photovoltaic electricity is also integrated with the methanation processes of CO2.

Energy harvesting

Specific topics addressed are devices containing cantilevers or polymers in reverse electro-wetting configuration that exploit mechanical or environmental vibrations, devices based on Spin-Seebeck effect or in magneto-caloric transitions to obtain electrical energy from temperature gradients, new devices for micro-generation applied to powering sensors or in general IOT devices using oscillating loads due to waves, wind or vibrations, based on embedding PZT devices.

Power grids

Activities focus on the design and the prototyping of electronic power converters with high dynamic performance and high efficiency for interfacing the smart micro-grid with the main power network, renewables sources, storage systems (batteries, supercapacitors), and loads. The activities concern the development of new control and observations techniques; new maximum power point tracking techniques (MPPTs), for PV/wind/marine current generators; new architectures for the electric energy distribution in smart micro-grids; energy management systems (EMS).

Micro-cogeneration

The studies are aimed at developing high efficiency, low cost, microcogeneration systems (MCHP) for smart-grid use, provided with electrical and thermal storage and powered by renewable and conventional fuels. The objectives concern: the development of single house MCHP (3.0 kW, high efficiency and low vibration),
the industrial development of a low cost 10 kWe MCHP, the development of a turbocharged super high electric efficiency 25 kWe prototype (> 35%) and the development of a super low cost 25 kWe system (<1000 €/kWe).

3. BIO AND ALTERNATIVE FUELS

The activity addresses the valorization of biomass, agro-wastes, wastes from industry, end-of-life consumer goods. A key topic is the production of gaseous and liquid fuels by thermochemical processes: pyrolysis yields solid (biochar) and liquid fuels (bio-oil), gasification converts waste into syngas. Upgrade of syngas and biooils is pursued by biotechnological and biorefinery processes: green diesel and gen III bio jet fuels from hydrogenation/cracking of microalgae; biodiesel by enzymatic lipase or from esterification of bio oils and bioethanol. Small-scale demonstrative units for reforming of biogas into a hydrogen-rich mixture are investigated and integrated with Fuel Cell. Other topics include biogas cleaning by functionalized carbon sorbents; catalytic (Rh based) reforming of biogas with residual H2S, H2S/siloxanes adsorption. The combustion properties of biofuels are assessed in lab-scale tests replicating real-life conditions; optimized solutions are defined for the utilization in i.c. engines (reciprocating and turbines). MILD combustion of torrefied biomass and biofuels is investigated targeting negative CO2 emissions. Other topics include the combustion properties and kinetics of gen II and III biofuels, their frame of knowledge being far from exhaustive. This frame includes the research on the production of micro-emulsions through micro-fluidic systems, and bio-slurry (dispersion of bio-char in bio or fossil oils), and the study of their combustion properties for the utilization in CHP systems.

4. CO2 CAPTURE AND USE

Research activities concern catalytic combustion of methanol, IGCC, oxycombustion, chemical looping, CLOU, chemical looping reforming, mild combustion, new catalysts and chemical carriers. Activities span from fundamental aspects to modeling, prototype development, and safety issues. Extensive research is carried out on CO2 capture: calcium looping, enzymatic capture, innovative CO2 sorbents for acoustic fluidized beds (MOF, GRM and magnetic materials). Activities aiming at post capture utilization of CO2 include purification of flue gases, enzymatic and catalytic conversion to methane or methanol. Advanced compact reactors for small-scale application are investigated, as well as integration with hydrogen coming from renewable solar source (Power to Gas concept). A simple scheme of integrated CaL-CSP process is suggested for the integration of CCUS in the energy grid. Other Integrated systems to be developed in the future activities are CO2 capture +solar and biorefinery and CO2 capture+chemicals production.

5 COOLING AND HEATING

**HVAC&R**

The activities concern: dynamic modeling of heat exchange processes and analysis and optimization of the air-side performances by experimental thermo-fluid dynamics; control of components and remote monitoring for operation; optimization of the overall efficiency of the electric drive moving the compressor; techniques for the minimization of motor’s electric losses (ELMT); pulsewidth modulation techniques (PWM) for the power converter; working fluids in HAVACR applications and PCMs for energy storage, also added with nanoparticles or nanoencapsulated.

**Diagnostics, energy saving and eco-sustainability in buildings**

Infrared thermography is used to measure thermal performances of building envelopes. Photocatalytic degradation of pollutants in air and in water is investigated. Energy management systems (EMS) targeting maximum efficiency of the building power plant are developed. Magnetic refrigeration is under development: it is a solid state technology based on easily recyclable magnetocaloric alloys and permanent magnets and uses water based fluids as heat vectors. The reverse operation allows for harvesting wasted heat.
**Solar cooling and heating**

Solar cooling and heating is studied for small-size residential and industrial buildings, based on an adsorption chiller and an electric heat pump. Innovative hybrid storage concepts for the Mediterranean and Continental climate are investigated, combining innovative adsorbent material for the surface heat exchanger with high density latent storage through an aluminum micro-channel heat exchanger with additional PCM layers.

3. **IMPACT**

**Impact 1: Expected impact of national and EU Set Plans**

DIITET research program contributes to realize the broader National and European energy and climate policy to achieve a European integrated and flexible energy system. Responding to the vision of a low carbon society, while at the same time safeguarding energy supply for all societal stakeholders, DIITET supports the development of technologies that enhance the share of renewable power (solar, wind, biomass etc), includes the use of clean fossil-based energy, in support of renewable energy sources and decarbonised industries. It includes a range of power generation technology sectors and ensures efficient CCUS (Carbon Capture Utilization and Storage).

**Impact 2: Developing critical mass of research capacity in Italy**

Putting together institutes of CNR with different expertise and funding opportunities, DIITET develops a critical mass and unique research capacity in Italy in the field of Energy technologies. This means to have the capability for solving the challenges facing the complex integration aspects in the current energy systems.

**Impact 3: Affirming CNR role**

Exploitation, dissemination and communication of results through third mission initiatives will increase the reputation and public perception of CNR and Italian Research in general. DIITET can be the interlocutor of National Public authorities and policy makers as regards energy issues.

**Impact 4: Internationalization**

Communication and transfer of the results in more academic contexts, through research publications and conferences, are the drive to foster national and international collaboration. Researchers of DIITET are already involved directly in several EU projects as well as active members of the European Energy Research Alliance’s Joint Programmes and national representative in international institutions (e.g., Mission Innovation, etc.). The projects carried out within the Department also explicitly sets out to bring on board a broader international energy R&D environment.

**Impact 5: Identifying gaps within national programmes/activities**

DIITET has already started to identify gaps within national programmes and activities. Currently, certain topics to be put in focus in the next 5-10 years have been identified:

**VALUE CHAINS:** Focus on value chains would be positive because it would allow to adjust and carry out the research in a way that will benefit individual components and whole process system and its integration into a wider system for production of energy, fuels, chemicals.

**ENERGY SYSTEM LINKING RENEWABLES AND FOSSIL FUELS:** Renewable dominated electricity production is key to realise the climate targets, but according to the Eurostat data of 2014 only 27% of the energy mix in Europe is based on renewables. The share of fossil fuel will be reduced further in the coming years, but the amount of CO2 emitted is still significant. Low cost and low carbon CCUS technologies and integrated value chains for CO2utilization can reduce the CO2 footprint of the European energy system, making sure the EU meet the COP targets and facilitate the needed security of supply.

**FLEXIBILITY IN THE ENERGY INFRASTRUCTURE:**
Renewable production of electricity is based on more and different power sources and due to the dependency on wind, solar and or tidal, it produces a non-programmable electricity output. Thus, fossil fuel utilization is a reliable back-up source of energy and CCUS technologies will be designed to generate this low-carbon flexible back-up power. DIITET will increase national and European focus on the mentioned topics, in close dialogue with relevant stakeholders. This will help to release CNR potential to becoming excellent in this field of energy research.

Impact 6: Fund Raising

EU calls:
Numerous calls in the field of energy are available in several funding frameworks as Secure, clean and efficient energy of Horizon 2020, or under the Programme Research Fund for Coal and Steel. They offer an efficient way for the funding projects in all the research areas covered by DIITET.

Other funding opportunities
DIITET has already undertaken initiatives to foster international collaboration and catch funding opportunities in other counties. Of particular interest the fast growing countries of China and Korea, as regards the development of clean coal combustion technologies, and South America countries for biotechnological processes. CNR could look with particular attention the opportunities of international collaboration coming from the huge Chinese funding from the One Belt one Road.

Impact 7. National Economy
Italy is a country characterized by an economy based on the transformation industry. The development of technologies for efficient and clean energy production from renewable sources has a double positive impact. Firstly, the increase of energy production from renewable sources lowers the import of energy sources, with a positive impact on the commercial balance. Secondly, if the capability to harvest and use larger shares of renewable energy at low cost will be increased, thus improving the competitiveness of the Italian products on the international markets. Not secondary is the impact on the national energy grid system: a target of the new generation energy production systems from renewable source is the increase of dispatchability levels. Finally, not less important is the capability to maintain a technological leadership in the sector of renewable energy, a prerequisite to sustain the growth of the companies that operates in this emerging sector of renewable energy, a task where the CNR can play a major role.

Impact 8. Societal impact
The diffusion of advanced energy systems can have several impacts on the society. Italy has been already subject to infraction procedures from the EU because of too high level of pollutant emissions. Ensuring a cleaner production of energy and ensuring lower consumption of fossil fuels is clearly a priority dictated not only by the undersigned agreements (Horizon 202020 and COP21), but especially to avoid the costly damage on public health.

Other costs in the use of renewable energy are being considered, as those associated with the grid imbalance, the need to shutdown conventional power plants with the negative effects on the employment levels in the large utility companies. Furthermore, it is emerging that not all renewable energy sources are equivalent to clean energy sources: proper processes are required to avoid the emission of pollutants or the disposal of end life wastes coming from devices for low carbon energy production.

Not less important is the sustainability of the sources that has already guided the introduction of rules for the production of bio-fuels.

These considerations clearly indicate the need of a correct strategy and the involvement of multidisciplinary research organizations, as the CNR, in the development of programs that sustain the transition to a low carbon economy.
4. EMERGING RESEARCH CHALLENGES

The priority challenge in the energy field is to meet increasing demand for energy while reducing emissions. This can be achieved by combining two technological issues: to use energy as efficiently as possible and replace primary sources with low carbon energies (including fossil-fuels power integrated with efficient CCSU operation). The efficient utilization of renewable non-programmable energy (wind, PV, etc.) places

the additional challenges of the storage of energy and the management of the energy fluxes and their integration in hybrid energy grids. This aspect opens to the challenge of the new millennium, e.g., the
digitization of energy. According to the BP Technology Outlook 2018, the digitization (sensors, big data, artificial intelligence, cybersecurity, etc.) could reduce energy demand and costs by 20-30% by 2050. The AP-LCT will promote a greater integration of the expertise inside the DIITET in order to face properly this stimulating multidisciplinary challenge.

5. CONCLUSIONS

The world is undergoing a radical transformation in the way energy is produced and used, shifting to a cleaner, consumer-centric and more efficient energy system. European countries, the industry, research organisations and the European Commission are working together to speed up this transformation. The goal is to facilitate the achievement of the EU climate and energy goals and to strengthen industrial competitiveness. This is being done by better coordinating national R&I agendas on low-carbon energy and mobilising the associated resources required.

The CNR and in particular the AP Low emission energy technologies (“Tecnologie energetiche a basse emissioni”) of DIITET are contributing to achieve the target that the national and European policies have fixed for a Secure, clean and efficient energy.

The research activities developed in the AP span from basic to applied science, from numerical modeling to complex experimental systems, with the aim of increasing the knowledge in the field of energy, energy transformation, energy systems. The numerous publications and participations in national and international projects, as well as in national and European networks and Institutions permits to DIITET to be a privileged observatory.

In the energy field the challenge to face in the next future is to meet increasing demand for energy at the same time as reducing emissions. The answer to such a dilemma is in the combination of two technological issues: to use energy as efficiently as possible and substitute the primary sources with low carbon energies. The research and the development of technologies able to contribute to the achievement of such issues will emerge as challenges in the future. In the next years, the decarbonization of the power sector will require a delicate transition passing through an integrated approach based on the use efficient and controlled of different and complementary primary energy sources. Such an effort requires combining expertise in chemical and mechanical engineering, chemistry, physics, materials science, biotechnology, information and communication technology, etc. The Department, with its broad spectrum of activities and expertise, is the ideal “environment” to carry out projects interdisciplinary at national and international level. The AP Low emission energy technologies could represent the core of expertise to stimulate and promote such initiative inside the DIITET and transversally to other Departments of CNR.
EXECUTIVE SUMMARY

The Institutes operating in this AP cover many research topics in the field of the green vehicles and sustainable transport system, in strict alignment with H2020 work program. The activities range from the scouting from fundamental studies of systems and processes (TRL1 – TRL2) susceptible for green vehicles application, to the development of advanced technologies (TRL3-TRL4), up to technology transfer for industrialization (TRL6). Research areas cover from the development of sustainable land-vehicles and water-vessels, to the support for the autonomous driving systems and signaling infrastructure for railways, and the monitoring of the environmental impact of the transport.

Each Institute, in its own specific area, operates at the state of the art of the research with a strongly focus on the most important current research topics. In the powertrain sector, huge efforts are addressed to the development of zero-emission systems with lowest possible environmental impact.

Here, IM, ITAE and IMAMOTER are strongly involved in activities related to the performance improvement of propulsion systems for future green vehicles for on-road and non-road, mobile machineries and marine application, such as battery and fuel-cell electric vehicles, fully environmental compatible combustion engines and hybrid architectures.

ICAR, ISTI and IMEM are involved on the intelligent transport systems and infrastructures, supporting the development of new solutions for the zero-accident mobility target, the implementation of policies for pollutant level reduction through the monitoring the environmental impact of traffic in urban areas and contributing to the improvement cost-efficient railways.

INM covers activities related to the environmental impact reduction from marine vessels, like hydroacoustic noise reduction during navigation, and the propeller efficiency improvement of the vessel with new super-hydrophobic surfaces with strong frictional drag reduction.

Consolidate cooperation and synergies exist among the Institutes, while, due to the fast technology evolution of this sector, new opportunities are expected in the next future. The existing multidisciplinary of the researchers and the availability of very important facilities and infrastructures makes the network unique in the national research community and competitive in a worldwide scenario.

1. STATE OF THE ART OF THE RELEVANT SCIENTIFIC AREA

A fast transition to an sustainable transport is one of the most important need of the XXI century. The transport system is facing a global and fast revolution in terms of manufacturing (Industry 4.0), zero-emission and GHG-neutral vehicles (including energy carriers), autonomous driving and connectivity and active safety. In this context the CNR plays a strategic role. The DIITET Institutes cover many research topics in the field of the green vehicles and sustainable transport system, in alignment with H2020 work program. The activities range from the scouting from fundamental studies of systems and processes at level of proof-of-concept (TRL1 – TRL2) susceptible of application to green vehicles, to the development of advanced technologies at TRL3-TRL4, up to technology transfer for industrialization (TRL6).

In the field of low or zero emission vehicles (IM, ITAE), a mix of technologies will be available in the mid-term future, increasing the presence of Battery Electric Vehicles (BEVs), Fuel Cell Vehicles (FCVs) and Hybrid Electric Vehicles (HEVs). Therefore, efforts are addressing to the improvement of BEVs and FCVs. In order to bring the internal combustion engines (ICEs) to be competitive with respect the e-mobility in terms of lifecycle CO₂ footprint, huge efforts are addressed to the development of quasi-zero emission fueled with fully renewable fuels. Relevant R&D activities are related to: innovative batteries and energy management, full electric or hybrid electric FC/battery powertrain, hydrogen and electric charging infrastructures for FCV and
BEV, pollutant-free combustion systems including the exhaust after-treatment. Green hydrogen and gas/liquid fuels (e.g. bio-gas, OME, etc.) will be produced from renewable sources for next-generation automotive powertrains. Anyway, open issues of the future sustainable vehicles still exist as: reduction of the capital costs and operating expenditures, reduction of CO$_2$ foot-print on the LCA, increase mileage range and robustness of BEVs and HEVs, development of ICEs with actual negligible environmental pollution. Fundamental remains the development of breakthrough technologies able to produce a relevant increase of the brake thermal efficiency of the ICEs (over 50-60%) and the total abatement of exhaust pollutant emission. The research efforts are also oriented to the development of **high efficiency and intelligent mobile operating machines** (IMAMOTER) for agricultural, earthmoving and material handling applications, where there are the same needs of decreasing emissions and enhancing automated functions, towards zero emissions and autonomous machines. However mobile operating machines are quite different from on road machines for their lower production volume and extreme diversification (architecture, mission profile, number of operating hours per year, etc.) then the solution must be tailored, cost effective and covering different technologies.

The operating machines are asked to work in a very unstructured and variable environment, with strong environmental disturbances for artificial sensory perception, thus making the task of implementing and training an autonomous control very challenging, often requiring an extended use of dedicated support infrastructures on the ground.

With respect to the **safety for zero-accident mobility** (ICAR, IMEM), the number of car accidents owing to driver’s distraction is a serious issue for society. Driver’s sleepiness, stress and fatigue are the major causes of several traffic accidents. The existing methods for measurement of physiological signals are bulky, uncomfortable, limited to few physiological signals. The efforts of the proposal are focused on using a non-invasive, comfortable and fully integrated system of innovative sensors, together with advanced techniques for multivariate signal analysis, capable of detecting and significantly reducing the role of the human factors in driving and interfacing with the advanced driver assistance system of the vehicle.

Such activities are part of the wider topic of the Advanced Driver Assistance System (ADAS), for which the **computer vision for autonomous vehicles** (ISTI) and the Monitoring environmental impact is a crucial research line. The advent of Convolutional Neural Networks has opened many opportunities for improving autonomous navigation systems based on computer vision technologies. Besides performing obstacle detection, computer vision allows to understand the scene in which the vehicle is moving, making possible to interact in a context-aware manner with the environment. This can have application scenarios for both ground and aerial autonomous vehicles. The management of traffic by using intelligent transport systems (ITS) plays an important role in the urban transports in order to optimize city transfers and reduce emissions. In this respect, the **monitoring the environmental impact of traffic in urban areas** (ISTI) and correlating it with other pollution sources is important to design and support effective policies for a cleaner city. Nowadays, pervasive sensor networks have been deployed making possible to create real time maps of urban pollution.

The family of green vehicles includes also trains, trams and metros are green and safe vehicles by definition. Looking at the **cost-efficient railways** (ISTI), the cost of the signaling infrastructure for these types of transportation means is relevant, and there is high demand for solutions that are able to drastically reduce costs. Reducing the wayside equipment to be deployed on the ground, and transferring control responsibilities onboard the trains, while maintaining safety, is regarded as one of the main research path to follow to decrease the costs of railway systems.

The theme green vehicles also covers the area of **efficient and low-emission marine vessels and ships** (INM). The area concerns the development of numerical and experimental tools aimed at the identification and characterization of the main sources of noise for a ship and the prediction of the concerned hydroacoustic field. For analogous propulsion devices (like aeronautical and marine propellers), the research has revealed some unexpected and essential differences between the noise generation in air and underwater related to the specific features and operating conditions of the device itself, which heavily affect both fluid dynamic and acoustic approaches. Recently, unconventional approaches based on simultaneous near- and far-field measurements in combination with conditional and advanced time-frequency signal decomposition techniques, have allowed to effectively address the diagnostics of generation and propagation noise mechanisms.
It is also still crucial to improve the propeller efficiency with new configurations and the development of fast simulation tools to be used at design stage. An open issue is the development of *ad-hoc* Super-Hydrophobic Surfaces (SHSs). Their drastically reduction of frictional drag (up to 35%) has been already demonstrated at lab-scale, but further studies are needed for the final application. Green marine vessels with low hydrodynamic resistance and high efficiency can be also achieved by simulation-based design optimization procedures. Open issues are the dimensionality of the design space, the accuracy and computational cost of the solvers, along with the extension to non-deterministic problems addressing a large variety of environmental and operating conditions.

### 2. CONTRIBUTION TO THE RELEVANT SCIENTIFIC AREA

In the following a short description of the main activities of each Institute in the PA Green vehicles is reported:

**ICAR**

Two main research topics are covered:

Zero emission and high efficiency propulsion. New electric KERS for internal combustion engine vehicles, which employs a super-capacitors bank (SC) as electric energy storage system, a motor-generator unit (MGU) to convert vehicle kinetic energy into electric energy and vice versa, and a power converter to manage power transfer between SC and MGU: the system was conceived to recover the vehicle kinetic energy during braking phases by charging the super-capacitor, whose stored energy is employed by the MGU for successive vehicle acceleration.

Safety for zero-accident mobility. To improve the design and development of a novel and high performance transport safety system improved through the adoption of human factors (HF), which combines optoelectronic sensors and bio-signal analysis techniques aimed at monitoring continuously the psycho-physiological status of the driver of a vehicle (car, motorcycle).

**IM**

Most of the activities are carried out in strict cooperation with the most important automotive, commercial vehicles, mobile machineries and supply component industrial companies in the world.

Looking at the sector of Internal combustion engines (ICEs), they have still a great importance in transport sector. Overall research activities are addressing to develop ICEs fully compatible with future stringent requirements in terms of LCA-based CO₂ footprint and negligible pollutant emissions.

Several technologies are under employing innovative numerical and experimental methodologies at the state of the art. Fundamental studies on liquid and gaseous sprays, in-cylinder combustion and new process sensors are continuously carried out in order to improve the control of engine functionality, while advanced numerical tools for combustion simulation are optimized and validated through the support of innovative diagnostic techniques applied to research engines.

The availability of physics and chemical laboratories for fundamental studies, research engine test cells, real engine test benches (light and heavy duty) and vehicle test dyno-chassis permit the study of new powertrains at different level of complexity: lab-scale for proof-of-the-concept, research engine for pre-validation and full-engine scale or vehicle for final optimization.

As regards the ICEs, the activities look at the development of advanced technologies for efficiency improvement in new generation spark-ignition engines (e.g. ultra lean charge, water injection, cooled exhaust gas recirculation), while new combustion system architectures and ultra-high pressure injection systems are some of the features under analysis for compression ignition engines.

In order to reach the negligible emission level of ICEs (e.g. NOx, particles down to 10 nm, etc., many efforts are addressing to the development of ultra-high efficient after-treatment systems (ATS). Finally, great attention is payed to the optimization of future ICE-based powertrains burning clean and fully renewable fuels (both liquid and gas).
Moreover, activities are carrying out on electric-battery and hybrid powertrains, as on the characterization of innovative fuel-cell systems.

In this respect, as for the ICEs technologies, lab-scale experiments are carried out for characterization, optimization and modelling of fuel-cell reactors and state-of-art energy storage systems (e.g. Li super-caps), while complete test benches (up to 300 kW) are available for electric powertrain testing.

**IMAMOTER**

IMAMOTER operates mainly in the sector of high efficiency and intelligent mobile operating machines. In this kind of machines the propulsion is just one of the several function of the machine, thus it is important to take into account of the energy behavior of the multiple functions and of the architectural complexity. Efficient Power Transmissions including Electric, Hybrid, Electro-Hydraulic transmissions and architectures for regeneration must be addressed. Holistic and distributed controls and new sensor are the key factors from implementation of automatic work tasks until the development of autonomous vehicles.

**IMEM**

The main IMEM’s contributions to the platform are related to the development, scouting and testing of state-of-the art devices, technologies and materials for applications in the mobility sectors aimed at increasing energy efficiency and safety and reducing carbon foot-print: magnetic materials and components for hybrid and electric motors, inductors and actuators, Current/magnetic field sensors, thermal and vibration energy harvesters. We also develop bio-sensors on organic cotton fibers for monitoring the health state of the driver (es. sweat and adrenalin).

**INM**

The INM activities are related to the prediction of the underwater noise from marine propellers and the acoustic mapping of complex, multi-body configurations, which accounts for the interactions of the propeller with hull, rudder, appendices, and for possible scattering phenomena. The analysis is carried out both in time and frequency domain, by coupling the acoustic solvers to suitable hydrodynamic simulations and pointing out the key-strengths and weak points of the different solving techniques. It seems also relevant to write down a reference text (currently missing in the literature) which summarizes the most significant aspects of noise predictions, shows the reliability of the various integral formulations and points out the differences between Aero- and Hydro-Acoustics. In the experimental field, standard methods have been integrated with unconventional approaches to establish source noise in a reverberant environment of a testing facility. Signal conditioning techniques based on synchronous near field and far field measurements along with advanced time-frequency signal decomposition methods have been employed for the analysis of noise generation and propagation mechanisms.

Numerical tools have also been developed to improve the efficiency of propulsion devices and, specifically, to better define the main characteristics of ducted propellers.

The study on SHSs is carried out in close cooperation with ISTEC-CNR, experimental tests are performed at high Reynolds number on flat surfaces using the INM high speed channel. Different water repellent surfaces are designed and tested varying the functionalization concept i.e. the viscosity of the liquid-solid interface and the surface roughness to identify the optimal surface parameters in terms of drag reduction and durability.

INM original contribution to simulation-based design optimization includes: linear and nonlinear design-space dimensional methods based on disjoint Hilbert spaces for shape modifications and significant distributed/lumped physical variables; adaptive multi-fidelity metamodels for uncertainty quantification and design optimization; single- and multi-objective hybrid global/local derivative-free optimization algorithms.

**ISTI**

Three main topics are covered by ISTI.

Cost-efficient railway: ISTI-CNR contributes with the application of formal and semi-formal methods to model and verify novel signaling solutions aimed at reducing deployment and maintenance costs for railways, to
guarantee safety and availability by-design. These solutions include the use of GNSS positioning of trains, moving-block technologies, distributed interlocking, and train platooning.

Computer vision for Autonomous vehicles: ISTI-CNR has developed models based on deep learning techniques for detection and classification of objects. The methods are suitable for deployment on embedded devices for on line and real time analysis of the scene.

Monitoring environmental impact: ISTI-CNR has contributed to the realization of pervasive wireless sensor network for traffic monitoring also based on smart cameras technologies. The network allows creating a real time evaluation of traffic, making possible to detect mobility patterns. Further work is in progress towards the evaluation of traces produced by individual cars in the city. Leveraging advanced imaging technologies, a proposal is being prepared in which each single vehicle is evaluated by analyzing exhausted gases in the plume.

**ITAE**

The main ITAE’s contribution to the platform are related to: the improvement of the performance of electric vehicles and their integration in the transport network; Development of innovative powertrains for BEVs, FCVs, HEVs with greater attention to electric hybrid powertrain (Fuel Cell/Batteries); Development of innovative batteries focused on electrochemical aspects and their performance such as power density, useful life, thermal management, waste heat recovery and valorization, safety and reliability; Development of battery monitoring systems (BMS), Modeling and simulation tools for BMS improvements; Tests, methodologies and procedures for the assessment of functional safety, reliability and duration of battery monitoring systems; Management and monitoring of the energy cycles of on-board storage systems; Conversion and storage of electricity used in different types of electric, hybrid and cogeneration systems; Integration of electricity conversion and storage systems with generation and / or propulsion systems; Development of on-board systems suitable to interface with infrastructures; Intelligent Transport System (ITS); Use of renewable energy sources for hydrogen and electricity production; Development of hydrogen vehicles high pressure storage (up to 750 bar); Development of hydrogen and electric charging infrastructures, recovery of heat from fuel cells for cabin air conditioning. CNR-ITAE is involved in four EU projects dealing with the production of green hydrogen and renewable fuels from CO2-H2 co-electrolysis for automotive applications. Efforts are addressed to reduce capital costs through minimization of expensive materials and through novel stack designs. Special attention is also addressed to solar hydrogen production using photo-electrolysis.

**3. IMPACT**

**ICAR**

Zero emission and high efficiency propulsion: the low complexity of the system proposed, the reduced volume and weight of the components considered for KERS assembly and their immediate availability on the market, make the solution ready for the introduction in current vehicle production.

Safety for zero-accident mobility. To increase safety in transport systems by early warning the driver and performing a safe stop of the vehicle, thus decreasing the number of accidents and raising the driver’s consciousness on her/his health and psychological conditions.

**IM**

ICE-based powertrains (both full-ICE, hybrid and plug-in) will represent the majority of the propulsion systems also in the long-term scenario (>80% in 2050 from IEA analysis). Even if the technology portfolio on the market will change from continent to continent and country by country, such foreseen will not change, also for the Italian case. Therefore, any technology improvement in terms of fuel consumption, GHG impact and pollutant emission reduction will represent an enormous contribution for the environment and will have a huge impact at scientific, industrial, social and political level. Simultaneously, the research on alternative zero-emission propulsion system must be strengthened in order to guarantee their market penetration as fast as possible.
From the point of view of scientific impact, the scouting of new breakthrough technologies from fundamental studies is the frontier of the research in this field, and the discovery of new solutions for future fully eco-compatible ICE-based powertrains and/or robust and long-mileage e-vehicles, it represents an extremely important task for the long-term sustainable mobility.

At the same time, the Europe and Italy, maintains a worldwide industrial leadership in the powertrain sector, therefore the technological advancement is absolutely strategic to preserve such position, and to expand it also to the most innovative systems (e.g. e-mobility). CNR institutes strongly contribute to this process through a relevant technology transfer activity to the most important OEMs of the sector.

Future eco-compatible vehicles have to be accessible from the majority of the population for personal and goods mobility, without any negative impact on human health and safety. Therefore, any effort addressed to the development of zero-emission and cost-effective technologies and/or eco-compatible energy carriers for the large-scale mobility will have an enormous impact at social and political level.

**IMAMOTER**

High Efficiency and Intelligent Mobile Operating Machines: The OEM of Mobile Machines must enhance their products implementing energy saving and intelligent control architectures to respond to the global challenges of lowering the emissions and increasing the safety of operators and the automatization of the work.

**IMEM**

Advanced magnetic materials and technologies are massively used in vehicles for the realization of components, motors, sensors, actuators, safety systems etc. Their optimization can have a strong impact in energy efficiency, safety and smart monitoring. Hybrid and multifunctional systems can be exploited in proof-of-concept devices and sensors to improve the driver safety (e.g. flexible bio-sensors).

**INM**

In recent years, the acoustic pollution of the seas and the environmental impact of maritime transport on marine fauna have represented themes of considerable interest. Not by chance, the EU financed several research projects focused on topics related to acoustics, not only for on-board safety and comfort issues, but also (and above all) for problems related to underwater noise. These topics are of critical relevance for the shipbuilding industry, due to the more and more stringent (national and international) regulations, which assume the noise as a quality-parameter of the marine environment and can even prevent navigation in specific areas. In addition, many important and strategic military issues are related to the underwater noise, concerning the ship's identification and traceability. In this context, the integration of numerical and experimental tools able to provide an overall, physically-consistent estimation of the hydroacoustic field appears, from both a scientific and industrial viewpoint, an essential resource.

The development of simplified numerical tools are aimed to provide fast predictions of the propulsive configuration in the preliminary design stage.

The use of water repellent coatings on the surface of marine vehicles can significantly reduce fuel consumption of surface ships and increase the mission range of underwater autonomous vehicles. Furthermore, they can potentially modify wake-induced vibration and cavitation inception for marine propellers increasing the ship efficiency.

Efficient approaches to simulation-based design optimization (design-space dimensionality reduction, adaptive and multi-fidelity metamodeling, hybrid global/local optimization methods) significantly reduce the computational cost of deterministic/stochastic optimization procedures of waterborne vehicles while retaining accurate performance predictions by high-fidelity solvers.

**ISTI**

Cost-efficient Railway: A reduction in the cost of railway transportation is expected to increase the diffusion of railways, and, in turn, the number of passengers and freight trains. This would lead to a reduction of road transport in favor of the greener railways.
Computer vision for Autonomous vehicles: Inclusion of advanced computer vision methods is expected to increase the applicability of autonomous vehicles to new scenarios.

Monitoring environmental impact: Although the long-term target is to have zero emission vehicles, nevertheless there is still a transition period in which accurate monitoring of the environmental impact of the current fleet will be necessary. Advanced technologies will be able to support adaptive policies for not exceeding allowed pollutants concentrations.

ITAE

The main impact of new technologies for a future environmental sustainable transport and green hydrogen technologies is on the reduction of the air pollution and environmental issues while contributing to mitigate climate changes. The technologies proposed are aimed to enhancing the potential of the RES plants by operating synergistically both on the hydrogen vector and on the electric energy. Regarding the production of Hydrogen from Electrolysis, in line with the National Strategic Framework (QSN) for compliance with the DAFI (Directive 2014/94 / EU) high-pressure storage systems will allow the use of distribution infrastructures to the FCV and HEV vehicles on the market (700 bar). Creation of new jobs, technology transfer from CNR Institutes to the co-operating companies, increasing knowledge, expertise and methodologies to speed up the design, development and validation of the enabling technologies for environmentally friendly vehicles in this field is another important outcome.

4. EMERGING RESEARCH CHALLENGES

Most important challenges in which DIITET Institutes are involved are:

- Zero emission and sustainable propulsion systems/vehicles in terms of CO₂ footprint;
- Safety for zero-accident mobility;
- Cost-efficient and intelligent Mobile Operating Machines;
- New material/sensors for green vehicles and marine vessels;
- High-efficiency ships and marine vessels;
- Advanced numerical tools for robust design and manufacturing of vehicles and vessels;
- New learning methods and artificial intelligent methods for autonomous vehicles;
- Intelligent infrastructure for cost-efficient railways;
- New methods for the monitoring of the environmental impact of the transport;

5. CONCLUSIONS

Institutes of the PA cover several and important research areas of the green vehicles, and they are well placed in the international scientific network. Most of the human resources are directly involved in powertrain development, in the broadest sense, from conventional Internal Combustion Engines to alternative zero-emission propulsion systems (Battery Electric Vehicles, Fuel Cell Vehicles etc.), while other important resources are directly involved in most recent emerging challenges, such as: low noise and high efficient marine vessels, autonomous vehicles, zero-accident mobility, intelligent infrastructure for mobility.

Consolidated cooperation and synergies among Institutes already exist, while, due to the fast technology evolution of this area, new opportunities are expected in the next future. The existing multidisciplinary of the researchers and the availability of very important labs and infrastructures makes the network unique in Italy and competitive in a worldwide scenario. Example are the potential synergies between the artificial intelligent methods under development for autonomous vehicles and the requirement of control tools for very complex hybrid powertrains, as the study of new intelligent sensors for the improvement of the control of connected vehicles.
All industrial players operating in the sector (from the automotive to the marine vessels) and the related infrastructure are involved in the evolution process of the transport system, characterized by a fast & ferocious competitiveness. Most of them are large multinational enterprises having consolidate cooperation with the Institutes of the PA. In order to expand and reinforce such cooperation, so increasing the CNR participation in the progress of the science and technology in this PA, the networking among the Institutes should be strengthened, with particular attention to the external communication of all activities toward the industrial partners.
AP19 MARINE TECHNOLOGIES

EXECUTIVE SUMMARY

The AP “Marine Technologies” conducts fundamental and applied research and technological developments with impact in a sustainable exploitation of the Ocean resources and in the Smart, Safe and Secure operations at sea and is involved to sustain the development of new regulatory frameworks and standards both at EU and International level.

The multi-disciplinary nature of the research challenges in the field of the green, smart, safe and secure exploitation of seas involve many branches of the engineering, such as materials, structures, hydrodynamics, hydroacoustics, electronics and automation, informatics…, and, thus, imply the AP to cluster skills and research infrastructures from different Institutes of the Department of Engineering, ICT and Technologies for Energy and Transportation: the Institute of Marine Engineering (INM) with competences in the area of naval architecture and marine engineering, the Institute of Information Science and Technologies (ISTI) operating in the field of computer science, the Institute for Research on Combustion (IRC) and the Institute for Research on Engines (IM) active in the key chemical and physical processes underlying energy conversion, the Institute for high performance computing and networking (ICAR) operating in the area of intelligent systems with complex functionality and high performance computing and the Advanced Energy Technology Institute (ITAE) active in developing innovative energy processes and technologies.

If the final research and technology targets of the AP "Marine Technologies" find their motivation in the current social and political challenges, the engineering problems worth to be addressed have a multidisciplinary and complex nature as described in the "State of the Art” section. This has pushed the Institutes to work on several topics and to reach significant results which are further detailed in the "Scientific Contribution to the Relevant Area" section. As highlighted above, beside the relevant scientific production, the AP "Marine Technologies" is active in supporting industry needs for edge technological solutions which are described in the "Impact" section. The long-lasting competence and continuous updating in knowledge and research infrastructures allows the AP "Marine Technologies" to be ready for future and, in some sense, visionary challenges as outlined in the "Emerging Research Challenges” section.

1. STATE OF THE ART OF THE RELEVANT SCIENTIFIC AREA

Oceans are increasingly the crossroads of the resources of the Earth both in terms of exploitation and transportation. Globalization and the global growth of the population have given a strong impetus to the centrality of the oceans in the economic and socio-political equilibrium, which however begins to clash with the primary role of the oceans in the eco-system. The request for a lower environmental impact and the improvement in activities related to the sea are the objectives that have guided research and technological development in past decades; more recently, also in consideration of climate change threats and opportunities.

The keywords for the development of maritime technologies have been Safety, Efficiency and Greening. However, it is not possible to reach significant targets (e.g., an efficient circulation of goods) without eliminating bottlenecks that exist in the whole process (e.g., shortening of cargo unloading and loading time requires up-to-date port infrastructures and inland logistics support). Thus, the integration of technological solutions developed in different sectors of maritime engineering becomes a key element: this is called an Integrated Mobility Strategy. This need for integration is also present in engineering activities concerning the exploitation of the ocean resources: the ocean space utilization within a maritime spatial planning includes energy (fossil and renewable sources), fishing, aquaculture and blue-technologies, hard infrastructures and transport services. The concept of greening widens up to sustainability; matching the environmental constraints in marine technology begins with the choice of materials and assembly techniques and ends with disposal and recovery, following the concept of circular economy. The safety concept currently develops beyond the use of accurate and robust predictive models for vehicles or offshore structures; the growth of
diagnostics and decision-making processes pushes toward the reduction of the human factor, using unmanned and autonomous systems, typical of robotics. This further underlines the multi-disciplinary character of ocean engineering, more and more developing under ICT paradigms.

The design, development and manufacturing of ship, offshore structures and on-shore installations involves a multi-disciplinary, integrated and highly complex set of processes and tools that embrace the whole product life-cycle. The process comprises many disciplines which depend also on the specific application: materials (material science), structures (theory of construction and structural mechanics), loads and performances (hydrodynamics, maneuvering, seakeeping and propulsion dynamics, station-keeping, control systems...), propulsion systems, energy generation and storage, automation, comfort, safety and security management. The global trend is towards the integration between digital design and digital manufacturing with the aim of improving quality, reducing costs, delays and reworks. The iterative procedure traditionally used in preliminary design is only partially able to consider all these disciplines in a holistic way and include new constraints due to climate change (increasingly harsh environment). Thus, there is a need to adopt knowledge-based strategies of analysis able to develop innovative concept design based on numerical simulations integrated in a multidisciplinary optimization procedure.

The conversion of energy into vehicle motion is a key issue for surface and underwater vessels as well. The objective is to lower the installed power on-board by designing low-resistance hull shapes on one side, to turn the mechanical energy into momentum change as efficiently as possible with propellers, waterjets, sails. The way this energy is produced makes the difference in classifying a vehicle as environmental friendly since ship exhaust emission causes environmental pollution, greenhouse gases and consequent effects on human health. Low carbon technology and ship electrification are alternative approaches to the same target. Decarbonization involves the development of a more efficient and green propulsion and power supply systems to enable navigation in Emission Controlled Areas. Liquefied Natural Gas (LNG) and/or biofuels (biogas, bioethanol) as fuel for efficient gas engines and in integration with Fuel Cell Systems can decrease the emissions of SOx, NOx, CO2 and black carbon and then the ship GHG footprint. The abatement of new target pollutants can be pursued by increasing the cleaning efficiency of the after-treatment units, also with retrofitting. The exploitation of the Waste Heat Recovery solutions is another way for achieving a higher energy efficiency. Concerning ship electrification current targets are related to use hybrid electric systems for inland waterways, fully electric vessels for urban waterborne transport and possibility of electric plug in for ships for switching off engines in harbors.

Reducing the shipping environmental impacts concerns also facing the problems of anthropogenic noise emissions as underwater noise has been included recently within the definition of pollutions. A joint effort between the marine and maritime research community is to define noise limits and dangerous frequency ranges, but at design level this is still an open problem due to limitations both in simulations and field data.

In a different perspective, the power management on-board contributes not only to foster the energy efficiency but also to guarantee the ship safety by powering critical on-board systems for navigation, cargo, weapons, and other operative functions. The Shipboard Power System aims to be self-adaptive and to play a more relevant role for the All Electric Ship, including propulsion.

In a connected and automated world, ship and offshore systems are designed as cluster of interacting subsystems, but at the same time are also the nodes of complex ocean networks. Nowadays, marine and maritime monitoring and surveillance activities are based on a wide availability of multi-sensor data, ranging from satellite data to ground based data, from radar data to the ones acquired by specific vessels. Thus, data interoperability, integration and security are among the main issues in designing Marine Information Systems and other platforms benefiting from ICT topics. As stand-alone systems, the availability of distributed sensing capabilities along with data fusion and machine learning techniques promises to enhance the safety standard on-board, promoting Predictive Maintenance and Damage Identification approaches.

To reduce the human factor in sea accidents, the purpose of operating large unmanned systems like cargos or small-scale passenger vehicles finds in marine robotics its precursor. Marine robotics requires the development of new tools, paradigm and methodologies for the autonomous cooperation of heterogeneous robots, even in the presence of manned platforms. Moreover, the complexity and cost of at sea operations
and the extension of areas to be explored and surveyed, as well as the needs of persistent monitoring and rapid environmental assessment, require the development and implementation of new operational concepts able to minimize the presence of support vessels in the operational areas and to improve autonomous underwater intervention capabilities introducing topics like cooperative robotics, sensing and perception, navigation, guidance and control, mechatronics and marine IoT.

2. CONTRIBUTION TO THE RELEVANT SCIENTIFIC AREA

Research and development activities within the AP “Marine Technologies” are addressed to four macro-areas including: (i) “Green transportation”, (ii) “Smart, Safe and Secure operations at sea”, (iii) “Advanced ship design, construction and performance improvement” and (iv) “Automation and connectivity”.

In the context of the eco-sustainability of maritime transportation, research pillars focus on the reduction of the environmental impact of marine vehicles, which comprises the themes of the low emission engines, the waste management and the impact on marine biodiversity, and on the improvement of the energy efficiency in the maritime transportation, which involves the performance improvement of marine vehicles and the processes of energy production, distribution, management and recovery. Technologies for low emission engines are strictly related to the development of environmentally-friendly combustion and catalytic processes (i.e. low temperature Selected Catalytic Reduction, catalytic oxidation, air purification, catalyst poisoning/regeneration), alternative fuels with low carbon and high hydrogen composition, dedicated internal combustion engines fed by natural gas or synthetic natural gas from biomass and waste as well as electric and hybrid propulsion systems targeted to reduce fuel consumption and pollutant emissions and to improve energy efficiency. These solutions are integrated with new technologies for electric and thermal energy production (e.g. fuel cells and reformers, renewable energy sources), thermo-valorization of wastes and biomass (e.g. onboard waste thermal treatment and gas phase waste heat recovery units, waste heat from exhaust recovery for air-conditioning and refrigeration purposes) and innovative on-board energy distribution and management systems. From the hydrodynamic perspective, the efficiency improvement of marine vehicles is related to the theme of the drag reduction, which is pursued through the reduction of the skin friction by water-repellent coatings (Super Hydrophobic Surfaces) and the optimization of the ship/hull/appendage design by the simulation-based optimization procedures in combination with advanced experimental and computational methodologies.

Besides the reduction of greenhouse gas emissions and oil pollution, there is a growing scientific attention into the problem of the underwater noise and its effect on marine mammals. Research programs have been developed and implemented to study the underlying mechanisms of noise generation and propagation from ship and shipping and to find operative and design solutions for mitigating underwater noise pollution without affecting the fuel efficiency of the propulsion systems. Hydroacoustic research is addressed by numerical prediction methods of the underwater noise generated from propellers and multi-body configurations, coupling the Ffowcs-Williams Hawkings (FWH) equation to suitable hydrodynamic simulations and mathematical methods to model and simulate noise propagation in the oceans, such as the Ray Theory. In the field of experimental hydroacoustics, research is mainly focused on unconventional approaches allowing a cost and time effective analysis of the underlying mechanisms of noise generation and propagation through signal conditioning techniques and synchronous near-field and far-field measurements.

Research on “Safe, secure and smart operations” involves the predictive maintenance of marine vehicles and infrastructures to prevent accidents and failures in critical components, the detection of malfunctioning and damages, the integrated control of the traffic including the presence of drifting objects, search and rescue of men lost at sea and the management of incidents and emergencies. The problem of the predictive maintenance is addressed by the accurate and reliable evaluation of critical loads on marine vehicles and infrastructures exposed to the effect of waves and currents under severe sea state conditions or operations, including those associated with the sloshing of ship tanks with Liquid Natural Gas or with the oscillations of pipelines deployed on the sea bottom or risers. These problems are addressed in a multidisciplinary framework that includes (i) emerging numerical methods, such as the Lagrangian Particle methods, for the prediction of the hydrodynamics loads in sloshing flows and impact problems, (ii) full-scale and laboratory
load and response models and correlation methods applied to critical phenomena on ships and offshore structures for the prediction of the safe operational margins and the remaining fatigue life and (iii) damage detection methods correlating the structural response to the presence of defects or damages in materials, components or machinery. Techniques integrating measurements and numerical models by data fusion approaches are specifically developed to provide an extended representation of physical phenomena (like slamming or other FSI problems) with the aim to further the understanding on the underlying mechanisms of fluid-structure interaction. Research applied to the integrated control of the traffic is focused on the design and development of technologies for vessel detection and recognition within a given area and for marine environment monitoring including the tracking of floating objects. In particular, research efforts are addressed to: (i) the implementation of a satellite imagery based automatic system with the ability to detect relevant anomalies such as unauthorized fishing or irregular migration and related smuggling activities, (ii) the development of an Environmental Decision Support System (EDSS) based on several heterogeneous data (e.g. multispectral aerial data, SAR satellite processed data, environmental data, dynamic data, AIS data) for monitoring and quantitatively representing risk factors and notifying events deserving consideration and (iii) the development of Lagrangian numerical methods for tracking floating objects under the effect of wind and currents. The trajectory prediction of persons at sea is an important topic also for what concern the emergency management along with all the issues related to the detection, isolation and reconfiguration of the Shipboard Power System (SPS). In particular, the reconfiguration of the Shipboard Power System (SPS) is a challenging problem embracing a multitude of possible scenarios, goals and decision-making procedures that is pursued by integrating a holonic multi-agent system for the self-adaptive composition and orchestration of services in a distributed environment (MUSA, Middleware for User-driven Self-Adaptation) with a virtual simulator of the electric system validating the reconfiguration plan (MATLAB).

“Design, construction and performance improvement of marine vehicles” is a wide multidisciplinary research area which includes computational and experimental hydrodynamics, hydroacoustics and hydroelasticity, metrology, material science, mathematics, electronics and engineering. In particular, the design and the performance improvement are central themes of fluid-dynamics and applied mathematical research including the development and application of: (i) innovative simulation-based ship design multi-disciplinary optimization procedures with uncertainty quantification and reliability-based robust optimization for the design of ship/hull/appendages subject to uncertainty, (i) novel design-space dimensionality reduction methods for shape optimization in ship hydrodynamics and multi-physics problems, (iii) dynamic/adaptive metamodeling and machine learning techniques for the affordable prediction/optimization of ship/hull/component performance and (iv) advanced experimental and numerical tools to support the design, the diagnostics and the performance improvement of marine vehicles for different operative scenarios. A non-exhaustive list comprises advanced methodologies for the study of fluid-structure interaction, advanced experimental and numerical tools for the analysis of the noise and vibration generation and their propagation inside and outside the vessel, experimental methods for the study of wall-flows (Temperature Sensitive Paintings), numerical and experimental methods for the fluid-dynamic analysis of complex flows such as those associated with cavitation phenomena and bubble dynamics, free surface, wave breaking, installation effects and unsteady flow problems (i.e. experimental techniques for detailed flow measurements, such as LDV, PIV, Tomographic PIV; potential and viscous solvers for CFD analysis, such BEM, RANS, DES, LES). Research in smart and innovative materials, such as super-hydrophobic paintings and composite materials, and in new manufacturing processes, such as those involving 3D printers, is undertaken through experimental tests about different water repellent surfaces and systematic test series along with finite element models. respectively.

In the context of “Automation and connectivity”, beside the aforementioned research and development activities related to the Shipboard Power System (SPS) and to the Environmental Decision Support System (EDSS), the theme of marine robotics represents a topical issue for ocean monitoring, exploitation and swarming. In particular, research efforts are focused on four topics: (i) the design and development of prototype AUVs, ROVs, USVs, and USSVs with particular attention to portable modular vehicles that can be easily reconfigured at field in different shapes (e.g. the POP-ART concept foreseeing a ROV, that can be reconfigured as AUV and/or USSV), (ii) the design and development of prototype multi-rotor UAVs for short range cooperation with USVs, (iii) the design and implementation of cooperative guidance and mission
control algorithms including cooperative landing of a UAV over a USV and (iv) the design and implementation of cooperative methodologies for seabed mapping and characterization, e.g. automatic detection of seagrass.

3. IMPACT

The research studies and the technological developments within the present AP have an impact at scientific, industrial, social and political levels. Scientific results are disseminated worldwide via publications and conference presentations and their impact has a transnational relevance. On the other hand, industrial, social and political aspects of the research are more inherently related to the granting institution (Italian government, EU commission) and, in the case of marine and maritime technologies, to the specific geopolitical context, that is, the Mediterranean Sea.

The AP “Marine Technologies” aims at exploring new research directions, developing innovative solutions and supporting intelligently the stakeholders for the design of products and services along two main directions: (i) the Blue Growth, as a relevant paradigm of the Green Economy, and (ii) the Smart, Safe and Secure operations at sea, implying also Clean as a bridging feature with the Blue Growth. The concept of Blue Growth adopted by the EU can be explained as a knowledge driven quantum jump in the exploitation of marine resources, qualitatively different from the current exploitation pattern and fundamentally aimed at improving the societal wellbeing. Blue Growth implies a drastic change in the attitude of operators in marine and maritime sectors towards a synergistic, non-conflicting and sustainable use of the sea, still allowing a significant growth. This is recognized as a global challenge but felt particularly relevant for the Mediterranean region, due to its long history of marine resources exploitation and increasing anthropic human pressure. Clean, Smart, Safe and Secure operations at sea is a topic dictated not only by common sense but also by precise indications provided by the EU Commission. The reduction of accidents has been a priority in last years along with the lowering of their consequences in terms of casualties, loss of properties and pollution. The recent issues related to counteract terrorism, be prepared to local conflicts or manage new immigration routes through the Mediterranean Sea have brought to the fore the need of strengthening security for surface vehicles or installations as well. The abatement of harmful emissions is a benefit investing the entire society, both in terms of human health and opposing climate changes. Facing the above-mentioned topics may turn into an economic advantage for our societies, and for Italy in particular. Moreover, increasing the smartness degree of transportation or the resource exploitation at sea can provide less-costly solutions for conventional activities, adds new capabilities to the same operations and follows the worldwide trend for a connected and automated world.

To be successful, the AP is involved in creating enabling and cross-cutting technologies; as a byproduct of this activity, the AP knowledge platform lays the foundation for supporting CNR as qualified contact-point for the decision-making process at political level on ocean technology related topics. From a technical point of view, the AP “Marine Technologies” is involved to sustain the development of new regulatory frameworks and standards at EU and International level (IMO). For instance, the AP “Marine Technologies” develops research to define the Energy Efficiency Design Index, a technical measure for GHG emission reduction, or to elaborate standards for the measurement of noise and pollutant emissions, upon which MARPOL rules are based. Its continuous involvement on problem solving and technology development provides also an added-value for high-level education, collaborating actively with national and foreign Universities in training young researchers and engineers in the marine technology sector. The researchers contributing to the AP are involved as lecturers and invited speakers in university courses and conferences, and relatively to the marine technology sector have participated also as chairmen of committees within supporting initiatives at EU level or scientific institutions like, e.g., ITTC (International Towing Tank Conference) and ISSC (International Ship and Offshore Congress). Because of its human capital and laboratories, the AP “Marine Technologies” has been able to participate to important research initiatives and projects, like EU and Italian funded projects, Joint Industrial Projects and many others.

The AP has been contributing to these topics strengthening collaborative research between Institutes and researchers inside and outside DIITET; indeed, innovative and feasible technological solutions for the sea
activities increasingly require multi-disciplinary skills and attitude to technology transfer, in order to reach a practical and lasting impact at industrial, social and political level. The AP activity is also based on an important network of research infrastructures, which shapes deeply its own way of pursuing its research objectives: (i) extensive use of experiments in its facilities and laboratories to validate first-principle simulations; (ii) capability of testing full-scale technological solutions including also open sea trials; (iii) support for industrial testing to improve the reliability and efficiency of vehicles, off-shore structures and renewable energy devices; (iv) involvement in metrology and in the definition of new measurement standards and techniques. The presence of these key research infrastructures is also one of the drivers which allows the AP “Marine Technologies” to cluster the efforts of academic and research institutions to participate to national and EU calls in the maritime sector or even to take part at higher level to the decisional processes or EU supporting actions for the definition of future research priorities.

The capability to develop numerical models is the premise to support system design in a more efficient, reliable and accurate way, as a specific mission of this AP to bring into consideration the interaction between systems and the sea environment. The continuous increase of this potential also along unexplored patterns has greater chances to meet the industrial needs for facing new problems related to innovative devices: as occurred in the past for the development of fast transportation solutions, nowadays marine robots, new support vessels for larger or novel off-shore installations, more efficient and silent propulsion are just few examples of industry-driven targets.

In a Green Economy perspective, new industrial possibilities may rise or be encouraged by the AP research activities, increasing also job opportunities or even re-inventing some professional roles. In this framework, some relevant cases for the AP “Marine Technologies” are: development of innovative energy technologies for transportation (low-carbon or zero carbon fuels, after-treatment and energy recovery systems, hybrid propulsion, All Electrical Ship, adaptive Shipboard Power Systems, energy storage, high-efficiency ships with combined production of electrical and thermal energy), mechanical and structural design of renewable energy systems (offshore floating wind-turbines, tidal and wave energy converters, multi-purpose platforms), new materials and developments in material technologies (hydrophobic coatings, self-cleaning and anti-fouling materials with less use of aggressive paintings), systems for environmental monitoring and pollution recovery (monitoring platforms for acoustic and chemical emissions, unmanned surface (USV) and underwater vehicles (AUV).

Many of the above activities have also an indirect impact on building the Big-Data world and, in this perspective, there is an ocean of data worth to feed machine learning processes. The Marine Information System is an example of this: its integration with Observational Networks and on-shore data centers allows for coping with environmental protection, detection of illegal and unauthorized activities, warnings on extreme events. The ship itself, which benefits from weather forecast, can be a node of an Observational Network devoted to sense metocean conditions by the concept of ship-buoy. The ICT competence provides the enabling technologies for the Big-Data infrastructure in the maritime sector. At a smaller scale, the ship itself or the offshore installations are more and more shaping as Big-Data islands. Increasing the passenger experience or his safety during a voyage is nowadays possible tracking his position, conditions and attitude on-board. Extensive on-board diagnostics through sensor arrays already have an impact in reducing unnecessary inspections or providing the early-detection of system failures, up to the management of emergency procedures; the analysis of collected data is also beginning to give further chances to update mathematical models and probabilistic design approaches.

4. EMERGING RESEARCH CHALLENGES

- Self-repairing materials
- Modular and reconfigurable ships and logistics
- Hybrid models, virtual sensing and data fusion
- Bio inspired design
- Big data
- Zero emission activity vehicles
• Fully recycled components (bio-composites)
• Additive manufacturing for metallic materials
• Artificial Intelligence for the applications in smart oceans (unmanned and autonomous ships, marine robotics, swarms...)
• Underwater smart and clean technologies for Ocean and deep sea exploitation
• Micro-drones for ocean swarming
• Floating cities

5. CONCLUSIONS

The AP “Marine Technologies” is deeply involved in promoting excellence in research, in the development of innovative technological solutions, and in supporting also at social and political level a sustainable exploitation of the Oceans.

Excellence in research is witnessed by the involvement of his researchers in terms of publications, patents and important roles in scientific Institutions at national, EU and global level. This has allowed the AP “Marine Technologies” to be successful in attracting grants which have contributed to strengthen its network made of skilled researcher, trained technicians and worldwide infrastructures.

The technology transfer and the multidisciplinary competence play a fundamental role in this AP. Predictive models and technological solutions developed in other fields need to be tailored for the specific needs of the maritime applications or combined into new frameworks built over different disciplines: fluid-dynamics, chemistry, materials and structures, electrical engineering and electronics, system theory, information theory and so on. The trend, as the emerging challenges demonstrate, is for an increasing integration between the different approaches to reach technological solutions which are Smart, Safe and Clean, where smartness assumes increasingly the meaning of automation and connectivity. This implies a considerable effort in “coupling” the different disciplines, which turns not only into understanding interactions and feedbacks, but also into having researcher skills in this AP focused in connecting ideas and theories. As a last point, the role of the research facilities for achieving relevant research targets and for supporting the technological development of marine technology and ocean engineering remains critical and asks to be further strengthened.
AP20 CONTROLLED THERMONUCLEAR FUSION

EXECUTIVE SUMMARY

CNR research activities in the area of Controlled Thermonuclear Fusion (CTF) are aimed at the realization by the mid of next decade of the experimental prototype of fusion reactor ITER, under construction in France; its scientific exploitation in the next twenty years; the construction of the demonstrator reactor, DEMO, which will feed the grid with the first fusion electricity around the mid of the century.

The Institute for Ionized Gases (IGI, acting in the frame of the Consortium RFX, CRFX) and the Institute for Plasma Physics “P. Caldirola” (IFP) participate, with ENEA, INFN and several universities, to the EU fusion programme in the frame of several EU and international collaborations.

The scientific and technological activities carried out by IGI and IFP are supported mainly by the EURATOM, via the EUROfusion Grant Agreement "Implementation of activities described in the Roadmap to Fusion during H-2020", for R&D and including the participation in experimental campaigns in EU fusion facilities, and the agency Fusion for Energy (F4E), managing the procurements of the EU in-kind contributions to ITER. CRFX is responsible of the construction in Padua of the prototype of the Neutral Beam injector for ITER, in collaboration with Japan and India. IFP and IGI also benefit of contracts directly issued by the ITER Organization (IO) for integration activities and collaborate with Japan under the Broader Approach agreement.

In 2018 CRFX with a pool of private companies obtained funds under the POR-FESR EU scheme for regional development to upgrade the experimental fusion device RFX-mod, operative in Padua.

In 2017 the Italian Government approved the construction of a new fusion facility, the Divertor Tokamak Test (DTT), proposed by ENEA, CNR, INFN, and the consortia CRFX and CREATE. DTT is considered a key device in the “Roadmap to the realization of fusion energy” to investigate the system of power exhaust to be implemented in DEMO, to mitigate the enormous thermal loads onto the walls due to the burning plasma. IGI and IFP contributed to the DTT proposal and are presently working to the definition of the design of the device.

IFI and IGI participation in the fusion programme ensures CNR to develop strategic skills in Physics and Technologies of CTF and support the national industries in the procurement of ITER components.

IGI and IFP are deeply committed in formation and training of young scientists and engineers to adequately prepare the ITER- and DEMO-generation.

1. STATE OF THE ART OF THE RELEVANT SCIENTIFIC AREA

In 2013 the long-term programme of the European fusion community has been drawn up in the Roadmap to the realization of fusion energy covering a multi-decade period and aimed at the scientific exploitation of ITER and the construction of the demonstrator reactor DEMO by the mid of the century.

The implementation of the missions of the Roadmap has been assigned by EURATOM to the European Consortium EUROfusion via the multi-annual Grant Agreement “Implementation of activities described in the Roadmap to Fusion during Horizon 2020 through a Joint programme of the members of the EUROfusion consortium”, supporting the R&D activities organized in projects and experimental campaigns on a number of devices. EUROfusion consists of 30 research organisations and universities from 26 EU member states plus Switzerland and Ukraine. ENEA is the Italian member of EUROfusion, and CNR (coordinated by IFP) and CRFX (including IGI personnel) participate to the programme as two linked Third Parties of ENEA.

The programme includes several lines of scientific and technological research activities characterized by a high level of innovation as the development of new materials which can stand the thermal loads produced by a burning plasma, comparable with those on the surface of the Sun, and intense neutron fluxes; the superconducting magnets under construction for ITER, the largest ever realized; the remote handling systems...
necessary for the manipulation of reactor components activated by neutrons; the advanced control systems necessary for the integrated functioning of all systems and sub-systems essential for the full operations; the multi-MW auxiliary heating systems consisting of neutral atom injectors with energies around 1 MV and of millimeter-wave sources (gyrotrons).

Besides the technological challenges, also Physics and modeling of fusion plasmas have an important role in the Roadmap, from the implementation of an integrated tokamak modeling tool to realize a ‘numerical tokamak’ with high predictive capabilities, to the EU contribution to the Research Plan of JT-60SA, from the development of diagnostics of burning plasmas to the modeling activities supporting the experimental campaigns aimed at the preparation of the operational scenarios in ITER.

Indeed, the European fusion strategy under the EUROfusion Grant includes a robust experimental programme carried out in several European and international magnetic fusion devices. The largest operating tokamak in the world is the European facility JET (UK), which is also the only fusion device where the radioactive isotope of Hydrogen, Tritium (T), an essential ingredient of the nuclear fuel (together with Deuterium, D), can be used. In 1997 16 MW of fusion thermal power were produced in JET for ~1 second against 22MW of auxiliary heating power in the form of neutral beam and radiofrequency injection, achieving an amplification factor of $Q\simeq0.6$. In 2020 a new experimental campaign in DT is planned in JET, which should demonstrate the fusion energy production in stationary conditions, still for $Q<1$, while $Q>1$ will be one of the missions of ITER.

In parallel to the JET programme, a coordinated set of experimental campaigns is carried out on the so-called Medium Size Tokamaks, Asdex-Upgrade (IPP, D), TCV (SPC, CH), MAST-Upgrade (CCFE, UK), and WEST (CEA, F), while for specific projects, other magnetic confinement devices are also exploited, the tokamaks Compass (IPP, CZ) and FTU (ENEA, I), the stellarator Wendelstein-7X (IPP, D), the reversal field pinch RFX (CRFX, I), the linear plasma devices MAGNUM- and PILOT-PSI (DIFFER, NL), and GyM (IFP, I).

An international programme has also been established among some of the ITER parties, that foresees the participation of European Researchers to the experimental campaigns in DIII-D (GA, USA), EAST (ASIPP, C), JT-60 (QST, J), K-STAR (NFRI, SK).

Finally, new devices are under construction with an important involvement of the Italian community. The Broader Approach (BA) agreement between EU and Japan, which accompanies the experiments on ITER towards a future fusion reactor, envisages a voluntary contribution of some EU countries, including Italy, to the construction of the tokamak JT-60SA in Naka, and the successive share of experimental time. In the frame of the BA, CRFX is committed to procure the power supplies of the control systems (already delivered and installed in 2015) and of the protection circuits of JT-60SA.

The new Italian tokamak DTT, proposed by ENEA, CNR, INFN, and the consortia CRFX and CREATE, is presently in the design phase. Its first operations are envisaged in 2025, and its main aim will be addressing the problem of power exhaust for DEMO. Around 2022-23 EUROfusion will identify, on the basis of the outcome of an ongoing multi-machine investigation, the divertor concept most suitable to mitigate the large thermal loads expected in the reactor and will support the installation of such an optimized divertor in DTT.

In 2012 in the frame of an international agreement among ITER IO, F4E, CRFX and the Indian and Japanese Domestic Agencies, CRFX started the realization in the CNR Research Campus in Padua of the prototype of the neutral beam injector which will be installed in ITER for plasma heating. The facility consists of the SPIDER negative ion source with an acceleration voltage of 100 keV, and of MITICA, the full size neutral atom injector with energy of 1 MeV for ITER. SPIDER will start its commissioning and operations in 2018, while first operations of MITICA are expected in 2023.

Since 2016 the RFX-mod experiment has been shut down in order to implement several upgrades, including substantial modifications of the magnetic front-end and improvements of the diagnostic systems, which will empower the experimental capabilities of the device. The modified RFX-mod2 first operations are expected in early 2020.

The long-term character of the fusion programme requires in parallel an intense activity of formation and training of new generations of scientists and engineers who should inherit and further develop the skills
grown in the European national fusion labs. A training fellowship scheme for physicists and engineers has then been implemented by EUROfusion in close collaboration with several national Universities and Polytechnics.

There is also a strong effort to involve industries in the fusion programme. The Fusion Industry Innovation Forum (FIIF) has been implemented by the European Commission in 2010, and later with the Roadmap to Fusion Energy the fusion programme has been re-oriented towards the design and construction of the prototype reactor DEMO, that should integrate the requirements and the principles that nuclear industry requires.

Moreover, the EU fusion labs have developed and are repository of the skills in science and technology of magnetic fusion, which are necessary to support the national industries in answering the calls for tender issued by F4E for the construction of the ITER components in charge to EU. Due to the productive cooperation between Italian research centers and the industry, in the last ten years the Italian high-tech companies have been awarde of European contracts by F4E for about 1 billion € out of 2 B€ granted to European companies. EU industries will be also involved in the construction of DTT.

Fusion turns not only out to be a unique scientific and technological challenge, but also to open a new “market” for high-tech industry.

2. CONTRIBUTION TO THE RELEVANT SCIENTIFIC AREA

Since their birth in the early 70’s, IGI and IFP were focused on plasma physics and engineering studies, joining the Association of Italy with EURATOM to investigate plasma applications to fusion. In the 80’s IFP started a close collaboration, still going on, with ENEA-Frascati, with the responsibility of implementation and of operations of the ECRH system on the FTU tokamak. Since 1996 IGI’s activities are fully integrated in CRFX, as its principal partner, providing 60% of the manpower; other partners are ENEA, INFN, Padova University and Acciaierie Venete SpA. Both IGI and IFP are strongly committed in the activities on the EU Tokamaks, and in developments for future devices: IGI/CRFX being responsible of the construction of the ITER Neutral Beam Test facility (NBTF), IFP with a strong involvement in the development of ECRH systems for ITER, DEMO, DTT.

At IGI/CRFX is also located the RFX-mod facility, exploiting the magnetic configuration Reversed Field Pinch to confine the plasma, alternative to Tokamak. IGI/CRFX is involved in BA activities for power supply provision for JT60-SA.

Collaboration to the ITER project:

IGI/CRFX hosts inside the CNR Research Campus in Padua the ITER NBTF set up to develop and optimize the prototype of the neutral beam injectors, one of the most important and critical components of ITER. NBTF comprises two experiments: SPIDER negative ion source with an acceleration voltage of 100keV, and MITICA, the full size ITER neutral atom injector with energy of 1MeV, both with 40A accelerated D-beam. SPIDER is starting the operation in 2018, while MITICA components are under construction, operation being planned from 2023. NBTF is a large facility with a total investment of 200 M€ from F4E, CNR and the Japanese and Indian ITER Agencies. About 50% of IGI personnel is involved in NBTF through F4E grants. IGI/CRFX is managing the facility, has designed, followed up the construction and commissioned the subsystems: vacuum vessel, RF beam source, accelerator grids, beamline components, vacuum and gas injection plant, cooling plant and cryogenics, diagnostics and data acquisition and control systems, source and accelerator power supplies. Physics studies of the accelerator and of the Cesium effect support the design. R&D on NBTF is accompanied by an extensive programme on local flexible test facilities to study the High Voltage holding up to 1MV, RF voltage hold off, Cs deposition (required for negative deuterium ions generation), and on the NIO1 small experiment to optimize source and accelerator. This is complemented by participation in R&D programmes on ion sources and beam injectors at NIFS and QST Japanese laboratories and at IPP-Garching in Germany. Collaborations for specific activities are setup with laboratories including CNR-Nanotech in Bari and IFP, which provides the neutron diagnostic.

IGI/CRFX works through direct contracts with IO on electromagnetic modeling of ITER passive structures and on design of the ITER core Thomson scattering and magnetic sensors.
IFP contributes to the ITER project with the design, optimization and realization of different components of the Electron Cyclotron Resonant Heating (ECRH) system, the first heating system which will operate on ITER in 2025. Up to 20 MW of millimeter-wave electromagnetic (EM) radiation at a frequency of 170 GHz will be injected in the plasma to assist breakdown, plasma current ramp-up and ramp-down, plasma heating, localized non-inductive plasma current generation to control MHD instabilities and for disruption mitigation. Under F4E Grants, IFP is responsible for the Physics and optimization of the ECRH Upper Launcher and for the procurement of the bolometric dummy load needed to dissipate MW-level EM radiation produced by the gyrotron sources. This technology, developed at IFP during two decades, is at the basis of the provision of several dummy loads to different international labs hosting fusion devices, as ENEA, IPP-D, SPC-CH, QST-Japan.

IFP participates also to the design of ITER diagnostics, the Plasma Position Reflectometer and the Gamma-ray Spectrometry system of the Radial Neutron Camera.

IFP has been beneficiary of contracts by ITER IO for the optimization of the Equatorial Launcher, for Physics-based transport modelling of plasma particles and energy, and for the design of the EC first Plasma Protection components.

For their expertise in plasma diagnostics, CRFX and IFP, in Consortium with two private companies, have been also awarded of a longstanding ITER Framework Contract for “Diagnostic Systems Engineering Services”.

Collaboration to EUROfusion:
Both IGI/CRFX and IFP are deeply involved in the EUROfusion R&D programme, supporting the Physics activities aimed at the preparation of ITER operations and the development of technologies in view of the prototype reactor DEMO. This programme is carried out in a wide European collaboration. The IFP and IGI/CRFX involvement in EUROfusion Physics areas includes the exploitation of EU tokamaks, with a strong commitment in terms of resources both on-site and at IFP and IGI premises. Such collaboration, including data interpretation by advanced modeling tools for particle, energy and momentum transport studies, covers the fields of control of disruptions and runaway electrons; impurity transport; preparation of next D-T campaign in JET; power exhaust; magnetic equilibria reconstruction; development of data access layers to support the data model of the infrastructure.

IGI/CRFX also collaborates to the Stellarator W7-X experiment by contributing to data acquisition and with the procurement of an innovative probe to diagnose the edge plasma.

The spectrum of IFP activities under EUROfusion extends to theoretical and modeling studies of electromagnetic radiation propagation in magnetized plasmas and of MHD plasma instabilities in tokamaks, as well as to data interpretation. The realization of the ‘numerical tokamak’ tool to support future devices design is being pursued in this context.

IFP also participates to the upgrade of nuclear diagnostics systems in JET, like neutron and gamma-ray spectrometers, crucial for the next DT campaign.

IFP also develops experimental studies on W erosion, material redeposition, ammonia formation in Needed D-plasmas, dust formation, migration and interactions, due to high plasma fluxes, which are carried out on JET and other tokamaks, and on the linear plasma machines MAGNUM-PSI, Pilot-PSI (NL), and GyM at IFP. Dust dynamics in the plasma is investigated by means of different numerical codes and compared with experimental data in JET. Plasma interaction at high fluxes with liquid metals is also investigated experimentally in view of their possible use in the DTT divertor.

A relevant activity, carried out both by IFP and IGI/CRFX, is the contribution to the preparation of experiments for the JT-60SA tokamak in the design of the ECRH and MHD control systems (IFP), in the procurement of the power supply for RWM instability control system and protection circuits (IGI), scenario developments, diagnostic design, database management (IGI).

The collaboration in laying the foundation for DEMO is carried out through the EUROfusion Power Plant Physics and Technologies Work Projects.

IGI/CRFX contribution is focused on: conceptual design of the DEMO Neutral Beam Injector; advanced diagnostic design; studies on the Plant Electrical System; optimization of the design of the toroidal field circuit topologies; design of large non evaporation getter pumps; studies on the role of fusion in long term energy scenarios and fusion power plant assessment.

In this frame, IFP coordinates activities aimed at defining the conceptual design of the ECR Heating & Current Drive system for DEMO.
In collaboration with ICMATE, IFP is involved in the mechanical and thermo-physical characterization of existing materials and alloys for structural applications in DEMO.

In past years, the experiments carried out on the fusion device RFX-mod led to the discovery of enhanced plasma regimes dubbed Single Helicity. This was possible thanks to a state-of-art real time system for the control of magnetic instabilities developed at IGI/CRFX. At present the device is being upgraded to further optimise the magnetic field error control and improve the plasma performance. The modifications are also intended to contribute to the scientific program of JT-60 SA for the magnetic unstable mode control.

All the experimental activities, both by IFP and IGI/CRFX, are supported by theoretical and modelling studies. The Divertor Tokamk Test (DTT) facility will be a large strategic research infrastructure, to be built in Italy in the next decade, with a financial contribution from EURATOM. It will operate for 30 years, in parallel to ITER and in view of DEMO. The main objective is to identify the most effective way to handle the huge amount of thermal power which will be produced in DEMO from fusion reactions. Due to the relatively low thermal power density hitting the walls, no fusion device presently operating or under construction, not even ITER, can face this issue.

CNR participated to the definition of the Project Proposal in 2015, and of its Business Plan in 2016, and presently is contributing to the pre-conceptual design of the machine. The skills grown up at IGI and IFP turn out to be of the utmost importance, mainly in (a) Physics and technology of plasma heating systems, by the injection of energetic neutral beams (IGI) and powerful millimeter-wave EM radiation (IFP); (b) design and realization of crucial plasma diagnostics (IFP & IGI) and (c) development of plasma active control systems, either via in-vessel magnetic coils (IGI) or by a local non-inductive drive of plasma current by means of ECRH (IFP).

Additional involvements of CNR in the project are in the preparation of operational scenarios, in the study of the edge and divertor physics, in the ELM and disruption mitigation strategies.

3. IMPACT

IGI/CRFX and IFP are among the major contributors to the international fusion programme, as host of the relevant ITER NBTF and of the upgraded RFX, as key parties in the DTT project, as participants, in collaboration with other EU fusion centers, to the development of several component and sub-systems of ITER, as leading contributors to Physics and engineering topics within a worldwide network of collaborations.

Two test bed experiments of the ITER most powerful heating system, the Neutral Beam Injector, are being realized in Padua under the leadership of IGI/CRFX, which is therefore responsible of one of the key systems of ITER, whose performance will critically depend on the reliability of such components. The construction of the two facilities involves several companies, Italian and international, and is carried out in strict collaboration with Japan and India.

Integration of several competences has been essential to the success of this project: thermo-mechanical and vacuum engineering, power electronics, in particular with RF and High Voltage expertise, IT and control systems engineering, modeling physics of the RF source and of the beam, diagnostics physics and engineering.

The mission of the NBTF facility extends beyond the development of ITER injectors, as it is meant to optimize the injector performance throughout the ITER lifetime and it represents the best environment to test new technologies, especially towards the future experimental reactor DEMO.

As far as the Physics activities are concerned, they are focused on critical aspects for future fusion devices, ranging from power exhaust to real time control, particle and energy transport studies, disruption control, MHD, edge physics, beam modeling, diagnostic implementation. They are aimed at preparing the operation of future devices: JT60-SA in Japan, DTT in Italy, ITER, and on the long-term DEMO. This regards naturally the activities related to NBTF and the involvement in the experimental campaigns in Tokamaks, but also the experiments on RFX-mod2, which will impact on key issues relevant for future devices, besides progressing the understanding of the RFP configuration fusion potentialities. IGI/CRFX pursues fusion power plant assessment studies through simulations of an RFP reactor and of an RFP based Fusion-Fission reactor.
The ongoing RFX-mod2 modifications have been funded (2M€ over a total cost of about 4M€) as a joint project by Consorzio RFX and a pool of three local companies under the POR-FESR European scheme, thus contributing to industrial innovation.

A great effort is devoted to the education of young scientists. Padua University and Consorzio RFX coordinate an International doctorate in Fusion Science among Padua University, Lisbon University, Ghent University. Master/Bachelor students, internships of master students summer stages of high school students are supervised by IGI/CRFX researchers.

Several outreach and communication activities are coordinated at IGI/CRFX within a science and society programme including tours and visits to the facilities, round tables, open days and events, which got a significant public response. Great effort continued to be dedicated to schools: as an example, 1008 students visited the laboratory in 2017, receiving a preliminary introduction into energy scenarios and fusion as a possible energy option for the future.

In the Eighties, IFP was given the responsibility to design and install the ECRH system, still operating on FTU (ENEA, Frascati), delivering 1.6 MW of EM radiation at 140 GHz for 0.5 sec, the most advanced ECRH system operating at that time. In the first decade of this century, still under IFP responsibility, this heating system has allowed to achieve in FTU several scientific results of high impact for the fusion community: record $T_e$ value of 14 KeV, development of ECRH modulation techniques for power deposition profile measurements, demonstration of plasma MHD instability feed-back control, proof-of-principle of the collective Thomson scattering diagnostic of Ti , demonstration of plasma disruption suppression, of saw-tooth period control, of EC-assisted plasma start-up, and of MHD real time control.

As a side product of the implementation of the ECRH system in FTU, IFP personnel started to develop a key technology for such plant, a bolometer load of new type capable of absorb and dissipate MW-level millimeter-wave radiation, and to give a measurement of the total amount of power generated by the gyrotron source by means of bolometric techniques. Over the years, in collaboration with an engineering design company, IFP, under EFDA and F4E supports, has developed several prototypes of bolometric loads, matched with the different technical specifications (frequencies, pulse duration, power) of the operating ECRH systems in the world, where they have been purchased and installed: in AUG in Garching, in TCV and the EU gyrotron test-bed in Lausanne, in JT-60SA in Naka.

Relevant scientific advancements in fusion plasma theory and modeling have been achieved mainly in two areas. The Physics of propagation and interaction of electron cyclotron waves in a magnetized toroidal plasma has been for many years a subject of theoretical investigation at IFP. A numerical code to describe the propagation and absorption of EC wave Gaussian beams in a magnetized plasma in tokamak geometry has been developed by IFP researchers and is presently recognized by the EU community as a benchmarking reference code for other models under development and is used in the optimization and design activities in the frame of EUROfusion and F4E ECRH-related activities on ITER.

A long-standing commitment of IFP Researchers in advanced numerical modeling and interpretation of discharges carried out in JET and other EU and extra-EU Tokamaks has allowed to deepen our understanding of the Physics underlying the processes of transport of plasma particles, energy, momentum, and impurities in the extremely complex system as a magnetically confinement fusion plasma, including turbulent processes. IFP maintains a key role in the international fusion community in this area.

An other area of excellence of IFP is the development of fusion plasma diagnostics. The expertise of IFP in millimeter-wave Physics and technologies has made possible to develop and install a prototype collective Thomson scattering diagnostic of the ion temperature in FTU, to design and install the Oblique ECE diagnostic in JET, to contribute under F4E to the design of the Plasma Position Reflectometry for ITER. The low-frequency instrument installed in the satellite Planck, to measure the CMB radiation, has been tested at IFP millimeter-wave laboratory.

IFP is a main center of competences in the development of neutron and gamma-ray diagnostics for fusion plasmas.
IFP in collaboration with ISM has developed a 12-pixels diamond based neutron spectrometer matrix. The first application of the diamond matrix will be the measurements of the 14 MeV neutron spectrum in the next DT campaign in JET. In JET IFP has designed and installed the gamma-ray spectroscopy and has the responsibility for the upgrade of the gamma-ray camera. IFP is responsible for the design of the gamma-ray diagnostic system in ITER and collaborates to the design and implementation of the neutron diagnostics for the NBTF in Padua and of a neutron spectrometer in EAST (in China).

IFP is putting a lot of efforts in dissemination of plasma and fusion science. During the years of activities under EURATOMIC programmes, IFP has begun collaborations with the University of Milano-Bicocca (UniMiB), with Polytechnic of Milan (PoliMi), and with the University of Milan.

Researchers of IFP are delivering courses on Plasma Physics, Fusion science and Plasma diagnostics at UniMiB, and students attend laboratory course using IFP facilities.

IFP has a traditional collaboration with UniMiB on neutron diagnostic development, and with PoliMi on investigations on plasma-material interaction. IFP has had and still have a key role in the increase of students in Physics and Nuclear and Material Engineering which are attracted by Fusion Science.

IFP organizes two Open-Days every year, which attract almost one hundreds students from the Universities and Polytechnic of Milan; it receives ten students per year from high-school in the so-called “Alternanza scuola-lavoro” project; participates to the “European Researchers Night” events in collaboration with the University of Milano-Bicocca and with then Polytechnic of Milan.

In 2019 IFP, in collaboration with the University of Milano-Bicocca, will organize the “46th European Physical Society Conference on Plasma Physics” (EPS2019), Milan, 8-12/7/2019, which will convene almost 700-800 scientists from all over the world.

4. EMERGING RESEARCH CHALLENGES

Being fusion at the forefront of Physics and of technological research, several emerging challenges are faced towards the realization of the reactor. As for Physics of burning plasmas, a coordinated set of experimental campaigns on the most performing fusion devices is carried out, accompanied by strong efforts in plasma modeling using high-power super-computers and as far as possible first-principle based numerical codes. The main technological challenge is represented by the enormous thermal energy fluxes produced by the nuclear reactions in the burning chamber. The aim of the construction of DTT is to develop and test the power exhaust system to be used in DEMO. IFP and IGI are deeply involved in the design of DTT.

Powerful heating systems are needed for ITER and DEMO. IGI/CRFX is building the PRIMA facility to test the 33MW 1MeV neutral injection system for ITER. IFP is working at the design and optimization of the ECRH system aimed at injecting 20 MW of radiation power in ITER plasma.

5. CONCLUSIONS

Controlled Thermonuclear Fusion (CTF) is considered by the most industrialized Countries and by those with the fastest economical growth as one of the most promising options to guarantee a long term, environmentally sustainable, almost inexhaustible base-load energy source to integrate the intrinsically intermittent renewable sources.

In H-2020 the EU research programme on CTF has been profoundly re-oriented towards the realization and scientific exploitation of ITER and to the design and construction of the prototype reactor DEMO, a strategic plan covering the first half of the century and described in the “Roadmap to the realization of fusion energy”. Italy is a leading actor at EU level since joining EURATOM almost 60 years ago. In the 70’s CNR started to be involved in fusion research via its Institute for Plasma Physics (IFP) and Institute for Ionized Gases (IGI), later entering the CRFX, investing important resources in personnel and in construction and operation of a number of facilities that have produced important scientific results at international level, and on which hundreds of
scientists and engineers have been formed, many pursuing brilliant careers in national and international research centers.

Due to the cross-cutting nature of fusion, other CNR Institutes have been later involved in EU programme, ICMATE, ISC, NANOTEC, SPIN, INO.

The increasing complexity of the fusion facilities and the decision taken in the first decade of the century of building ITER have motivated a closer and closer involvement of high-tech and innovative industries.

The Italian research-education-industry system in CTF has grown including the main public research bodies, several Universities and Polytechnics, establishing a number of new plasma physics and fusion science courses. In 2016 EUROfusion has listed more than 40 CTF-related PhD Thesis in progress in Italian Academic and research centers.

This community has successfully supported the national industry, which has proved to be the undisputed champion in the construction of ITER components.

The construction by CRFX of the SPIDER negative ion source and the procurements of JT-60SA components under the Broader Approach are a demonstration of the successful cooperation between national industry and research centers.

The next challenge for the community will be the construction of DTT, which will represent the most advanced operating European tokamak in the next thirty years, in parallel to ITER, and in view of DEMO.
EXECUTIVE SUMMARY

Mathematics is a fundamental science with extreme versatility, which is nowadays used in a range of frameworks that extends well beyond the traditional ones, such as physics and engineering. Its use encompasses biomedical science, environment, social sciences, industrial processes, administration, complex systems and many other fields. To be understood, modelled and managed, a world which is more and more digitalized requires an increasing formalization. The ever expanding use of mathematics stems from the combination of powerful computational systems and humongous quantity of data, while the challenges which mathematics faces today are leading to an expansion of its disciplinary foundations, which, in turn, results in an ever increasing reliability and methodological adequacy.

The research activities carried out in the institutes which are contributing to the AP Applied Mathematics, besides the natural interaction with the ICT sector, require a mathematics that, unlike the traditional academic discipline, can cover the whole pipeline of applied research, from the real life problem to its formalized modeling, followed by the development of ad hoc solution methodologies, the realization of a computational framework, with the engineering of the algorithms and, finally, the processing and interpretation of the results. The researchers at CNR bring forward a mathematics that is a driving force, able, with the outcome of their research, to anticipate and steer the needs of the different applications.

The goal that we are pursuing is twofold. On the one hand, we aim at developing, analysing and implementing innovative methodologies in different fields of applied mathematics. On the other hand we want to study its application in different frameworks: in those fields where the problems are already posed in “mathematical form”, with the engineering of alternative, more robust and efficient formulations, the use of state-of-the-art methodologies and the “certification” of the results; and in fields where the problems are not yet described in “mathematical form”, with a multidisciplinary approach and the contribution of our expertise in modelling and, afterwards, the development of analytical and computational solution tools.

Credits: Paragraphs 1. STATE OF THE ART and 4. EMERGING RESEARCH CHALLENGES have been built on the basis of the results of the online consultation on Mathematics carried out in 2016 by the DG CONNECT (European Commission Directorate General for Communications Networks, Content and Technology) in the context of a more general consultation aimed to prepare the Horizon 2020 Work Programme 2018-2020.

As reported in “Mathematics for Europe”, June 2016 (copyright: European Union).

1. STATE OF THE ART OF THE RELEVANT SCIENTIFIC AREA

Mathematics is a prerequisite for contemporary development in most fields of science. It is essential for both the exploitation of big data and the development of HPC towards exascale and quantum. At the same time, these developments are also enablers for new mathematics.

Data analysis, Topological applications, Mathematics for HPC, Complexity, Finance mathematics, and MSO (Modelling, simulation and optimisation) are important areas in being. Biomathematics is also emerging as a new prominent area.

At present time, most results are concentrated on new and emerging mathematical areas needed for the development of HPC, data or better simulation tools. Among these, we find tropical mathematics (algebra and geometry), algebraic-topological-geometrical methods for data analysis, approximate inference methods, stochastic geometric mechanics, integral biomathics, theory of evolving systems, etc.

Also probability, statistics and financial mathematics are indispensable, with new challenges requiring new approaches. Block-chain, trading algorithms, actuarial challenges of tackling big data and its implications for needs for inverse probability theory approaches, are certainly important for the society at large.
Artificial intelligence, robotics and complexity theory as a whole are also fields that require very high level mathematical input and are very important for Europe and for the European Science and Innovation.

The latest publication by the European Science Foundation on “Mathematics, its use and benefits for Europe” highlights success stories on the collaboration of mathematics with industry. Remarkable improvements have been possible in the design, planning and implementation phases of the industrial or service processes, leading to considerable savings and an increase in productivity.

Various areas are listed:

- automotive industry (software for simulation of spray painting, improved automotive injectors, designing oil filters, accelerated simulation, acoustic car design, computation of optical free-form surfaces);
- manufacturing (numerical simulation for the aluminum industry, imbalance estimation in rotating machinery, modelling and optimal control of chemical mechanical planarization, anti-reflection coatings, modelling plasma PVD, improvements in semiconductor crystal production, numerical simulation of metallurgical processes in silicon production, optimal utilization of colored gemstones, simulation of polymeric textile products, modelling and analysis of rotary fiber spinning);
- aerospace and electronics (modelling and simulation of spacecraft charging, flow control of an air duct, aero-engine nacelle acoustic treatments, reduction of testing by developing new ways of simulation, low cost airborne laser fly, simulation of stochastic radar signals, optimization of satellite coverage, simulating rowing boats, waves for ship-simulation, better prediction and understanding of rogue waves, sails modelling, mathematical modelling of complex materials in underwater sonar systems, optimization algorithms in electronics design automation, mathematical modelling of charge transport in semiconductors, online simulation of 3D nano-optical components);
- energy (bentonite buffer in nuclear waste management, intelligent video understanding applied to plasma facing component monitoring, modelling coal combustion, optimal flames in industrial furnaces, optimizing a complex hydroelectric cascade in an electricity market, mathematical models for oil pipelining, improving the simulation of multiphase flows in pipelines, intelligent agent based modelling and simulation of electrical grids, a kinetic model of blast furnace automation, numerical modelling of heterogeneous porous media, aero-acoustic virtual design of exhaust systems);
- environment (modelling and simulation of environmental problems, predicting climate change, solving underground water problems, simulation and optimization of waste water filtration, solar reflector design, simulation of a moving bed reactor used in the pulp and paper industry, dynamic image based lighting for highly realistic lighting in building design);
- health (optimization of radiation therapy, simulating atrial fibrillation, realistic modelling of human head tissues exposure to electromagnetic waves, mathematical modelling of a decontamination process, mathematical modelling of an ultrasound sensor for bioprocesses, minimal paths and virtual endoscopy, simulation of a bone-prosthesis system, unravelling the genetic code, forecasting for urgent medical care call centers, 3D X-ray imaging for dentists, computer simulations in electrocardiology, non-Fickian diffusion in polymers and medical applications, statistical testing of molecular motion inside living cells, non-invasive test for monitoring diabetes, early cancer detection by proteomics fingerprinting);
- services (tool for population pharmacology, shopper behavior modelling, generation of assignments of products to consumers, geo-temporal exploitation and analysis platform, analysis and forecasting the evolution of human potential and the job market, the use of queuing theory to increase the effectiveness of physician staffing in the emergency department, air elimination in milk pump systems, optimal portfolio mix using insurance market data, new approaches to reinsurance risk calculation, use of mathematics for transport networking, improving cable network capacity, making smart phones even smarter);
- transport and logistics (optimal trip planning in the presence of random delay, aircraft icing solutions, optimization of the emergency management systems, optimization of public transport systems, forecasting model selection in fast moving consumer goods supply chains, increased efficiency in air traffic control, truck load analysis, calibration procedure for a height measurement system for
excavators, crew rostering (scheduling), preventive maintenance optimization of trains air conditioning systems, optimization in sea logistics, control of navigable rivers, liner network modelling, contributing to the building of the digital society);

- other domains (optimal financial portfolios, financial derivatives pricing, pricing model of catastrophe bonds with complete calibration procedure, quantifying the liquidity premium in bond spreads for insurance liability valuation, modelling and forecasting stock price behaviour in high frequency trading, the resource valuation and optimization model, realistic assessment of financial products, model based optimum design of experiments, solution and model appraisal in reservoir inverse problems using global optimization methods, modelling and assessment of maintenance efficiency of repairable systems, optimization of electricity production, virtual piano based on mathematical modelling, secure communication for automatic teller machines, uncertainty assessment in high-dimensional nonlinear inverse problems, modelling and detection of realistic human actions in video, real-time video distortion correction, cognitive vision, handwriting recognition).

Interestingly, the largest computations in fluid mechanics in the world and one of the biggest computational capacities nowadays is in Hollywood (US). The film industry is running enormous simulations of flows, for instance to represent realistic-looking sea, waves, rivers, or to imitate real-life behaviour and produce other remarkable visual effects.

2. CONTRIBUTION TO THE RELEVANT SCIENTIFIC AREA

**Modellistica e calcolo scientifico**

**IAC**

**Mathematical and numerical modelling**

in the context of Continuum Mechanics and Fracture, Biology, Medical Sciences, Physical Chemistry, Ecology ..., either as fundamental research and for problem solving.

Mathematical modelling, numerical methods, optimization techniques and simulation for particle systems and fluids in classical, quantum and relativistic conditions with applications in: Theoretical, Applied and Computational Fluid Dynamics, Statistical Mechanics, Porous Media, Multi-Phase Flows, Material Science, Engineering, Cosmology, Environment (Hydrology, Glaciology, Pollutant extraction from soil, Collective behaviour of intelligent individuals, Traffic flow, E-Mobility) at any scale, from Macro to Atomic Scale, Nuclear and Sub-Nuclear.

**Qualitative study and numerical analysis**


**Numerical methods, algorithms and High-Performance Software**

for Sparse Linear Algebra, Predictive Simulation Science.

**Data, signal and image analysis**

Variational methods, multi-resolution analysis, non-linear approximation for image analysis.

Mathematical models, accurate and efficient algorithms and software for data analysis and signal processing.
IASI

Biomathematics
Simulation and analysis of stochastic differential equations models of integer and fractional order; Structured Partial Differential Equations models; Statistical Estimation of parameters for deterministic models and SDE models

IMATI

Analysis of PDEs
Optimal Transport problems and their entropic regularizations; analysis of transport equations with low regularity coefficients; non-local conservation laws, i.e. involving averaged velocity fields, which appear in models of both pedestrian and vehicular traffic; boundary conditions for systems of conservation laws;

Novel multifunctional materials such as shape-memory and magnetostrictive alloys.

Numerical Methods for PDEs
Treatment of complex geometries (the virtual element methods. Isogeometric analysis). Mesh adaptivity based on geometric and PDE-based criteria (e.g., geometric mesh quality, approximation accuracy, numerical stability)

Geometric and numerical methods for the multi-resolution representation and approximation of geometric data and scalar/vectorial design of preconditioners (domain decomposition, multigrid).

Uncertainty Quantification: collocation methods for UQ; Sparse Grids/Multi-Index Stochastic Collocation.

Computational topology and geometry
Geometrical and topological methods cellular and simplicial complexes, discrete exterior calculus, differential topology, Morse theory simplicial homology group computational algebra (splines, B-splines, extended Hough transforms) to curve fitting over (non-planar) surfaces.

Image processing
Development and comparison of image metrics, Wavelet methods, Image registration, Image classification, Image similarity assessment.

ICAR

Mathematical modelling and Scientific Computing
Focus on Problem Solving with methodologies that include computational simulation, scientific modeling, analysis, processing, and management of complex, heterogeneous, and large data sets. These methods integrate high performance computing (HPC) and distributed computing, with Computer Science, Applied Mathematics, and Statistics expertise. By appropriately integrating the methodologies with the knowledge of different application domains, we provide a new and more effective perspective for the analysis of real-life problems and the interpretation of results.

IIT

Algorithms and computational mathematics
This research group investigates models and algorithms for the solution of complex problems arising in some topical applicative areas, such as Web Information Retrieval, Computational Biology, algorithmic for Wireless Networks and Smart Mobility. These activities are also complemented with basic research activities in the field of numerical linear algebra.
ISTI

Computational mechanics

ISTI carries out research and software development in the field of mechanics of solids, with a particular focus on structural engineering, with the development of the Finite Element code NOSA-ITACA.

Computational topology and geometry

Analysis of visual data based on concepts from differential geometry, differential topology and algebraic topology; Group-invariant Persistent Homology and its use for Topological Data Analysis.

Sparse Image Representation and Dictionary Learning

Efficient representation of high dimensional data generated by a multivariate linear model, driven by a small number of basis or regressors.

INM

Computational fluid Dynamics

Advanced numerical techniques for Marine Hydrodynamics applications. Lagrangian and hybrid Lagrangian-Eulerian particle methods; Diffused Vortex Hydrodynamics; flows characterized by breaking waves and high free-surface deformations; flows around complex bodies

New models for the Optimization of Ship hull novel design-dimensional space reduction methods for shape optimization in ship hydrodynamics and multi-physics problems. Dynamic/adaptive meta-modeling and machine learning techniques and global derivative-free bio-inspired optimization algorithms have been

Evolution of viscous Newtonian fluids over a superhydrophobic surface

Hybrid BEM/RANS coupling Development of the CFD solver Xnavis/PRO-INS for the Hydrodynamic Analysis of Marine Propellers.

Development of high-Reynolds model for LES Analysis of the performances considering high Reynolds flows around naval geometries (submarines). Development of wall model functions for high-fidelity LES simulations.

Development of a non-standard ‘immersed boundaries technique’ in the curvilinear viscous high Reynolds number solver Xnavis.

Development of a general purpose gas-dynamic solver including high order spatial and temporal discretization schemes, AMR techniques, immersed boundaries approach and two phase flow capabilities.

Optimization and Discrete Mathematics

IAC

Mathematical optimization, control, game theory and decision-making science.

Discrete mathematical modelling, discrete structures, applications of graph theory, meta-modelling, study of computational complexity of algorithms, approach to constrained and unconstrained problems, methods of linear and nonlinear mathematical programming, methods of linear and multilinear algebra and numerical linear and multilinear algebra.
IASI

Optimization

A Two-Stage Robust Optimization scheme to shift scheduling and nurse-to-patient assignment and studying different versions of robust network loading problems.

Network Optimization problems: analysis of theoretical properties and development of solutions algorithms for network loading, capacitated network design, hierarchical networks, wireless problems.

Bilevel optimization problems in job shop and network design.

Mixed-Integer Nonlinear Optimization with Semicontinuous Variables: Perspective Reformulations, solutions methods, semi-infinite reformulations, quadratic reformulations.

Direct Methods: Derivative-Free solution methods for Nonlinear Optimization problems. These are methods that can be applied when derivative are either not available or very time-consuming, e.g. in black-box optimization and simulation-based optimization.

Discrete Mathematics

Polyhedral descriptions of the Stable Set polytope for claw-free graphs and other classes of graphs; Solution methods for the Max-Cut problem: different approaches for dense graphs of medium size and for sparse graphs of very-large size graphs.

Graph coloring problems: theoretical properties and solution algorithms for node coloring, edge coloring, total coloring, sum coloring.


Natural Optimization Algorithms. Rigorous mathematical analysis, that in a network setting, Physarum polycephalum’s dynamics are able to compute almost-optimal solutions to shortest paths and network transshipment problems on any weighted network. New Nature-inspired solution methods for Linear Programming and Convex Optimization.

Modellistica stocastica e analisi di dati

IAC

Applied and theoretical probability

Dynamical processes on Random Graphs, gaussian and poissonian approximation of Random Walks and point processes.

Data and Signals

Statistical models, algorithms and software for data analysis.

Accurate and efficient algorithms for signal processing. Information Theory, Big-data analysis, multivariate analysis, dimension reduction, Bayesian statistics, machine learning; computational pipelines for analysis and integration of data from Next Generation Sequencing.
**IMATI**

**Space and time stochastic processes**


**ISTI**

**Stochastic modeling of complex systems**

Stochastic models of random (mono- or multi-dimensional) signals generated by *complex self-organizing systems* (e.g., biomedical signals), with particular attention to *intermittent (possibly hidden) behavior*.

**System Theory and optimal control**

**IASI**

**System Theory and optimal control**

State prediction for nonlinear stochastic differential systems; Block-tridiagonal state-space realization of Chemical Master Equations (CME); Modeling biological timing and synchronization mechanisms by means of interconnections of stochastic switches.

**ICAR**


**IEIIT**

Modeling, analysis, Inference and optimization, and *control of dynamics over networks and Markov random processes*.

**3. IMPACT**

Examples of the impact of the CNR activity in Applied Mathematics is given by the following applications

**IAC**

- For the *Design and manufacturing of new soft mesoscale materials* with applications in *Tissue engineering, Photronics*, an ERC senior grant (COPMAT) has been awarded to S. Succi. This is supporting a research group working on the full-scale mathematical modelling and numerical simulation at nanometric resolution of microreactors for the design and synthesis of new tunable porous materials.
- Mathematical and numerical modelling of the coupled system, Atmo-, Hydro-, and Cryosphere, for prognostic and diagnostic study of *Climate Change impacts*. 

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- In Epidemiology, accurate forecast of an Epidemic behavior and more appropriate Control actions are the main target. A contribution in this direction to the development and analysis of mathematical models for waterborne infections and diseases is expected, possibly with the inclusion of random effects.

- Mathematical models and algorithms for the description and control of flows describing Collective behaviour of intelligent individuals (cells, cars, people) in heterogeneous environments.

- Mathematical modelling and support to signal and data processing for Complex Biological Systems (for disease diagnosis, medical therapy upgrade, process understanding at intra/extra-cellular and systemic level).

- Mathematical models and computational methods for data analysis, signal processing and image analysis applied to Cultural Heritage, Environment (remote-sensing data for Earth Observation and atmosphere modelling, applied meteorology, climatology, data from atmospheric multiple scattering, pollutant detection), Security and Defence, Health and Biology, Material Science, 3D Printing

- Partial differential modelling and numerical simulation for chemical damage forecast of artifacts aimed at conservation and protection of Cultural Heritage.

- Processing, exploration, analysis and knowledge extraction from Complex, Etherogeneous and Multi-Dimensional Data.

- Mathematical models and methods for Economics, Actuarial Sciences and Finance

- Application of optimization methods in support of decision-making in the context of Social Systems, Intelligent Transport, Advanced Sustainable Logistics, Management of Safety, Security and Emergency, Supply Chain in Agri-Food

- Mathematical models for Social, Biological and Technological Networks, and quantitative study of the main performance measures.

IASI

Applications of technologies developed at IASI include:

Optimization Applications in Power Energy Production, Network Design Problem, Sensor/Facility Localization, Portfolio Optimization, and others.

Modeling the probabilistic behavior in biochemical networks.

Modeling of biological timing and synchronization mechanisms by means of interconnections of stochastic switches.

IMATI

Application areas of the methodologies developed at IMATI include:

- Life sciences: simulation of blood flow in the brain, simulation of tissue perfusion in the eye, simulation of the electric activity of the heart, study of gene regulatory networks

- Automotive industry: study of contact problems for tyre design

- Smart materials: simulation of shape memory and magnetostrictive alloys, simulation of electronic nano devices

- Project and process management, in different frameworks, from ecology to Smart-care and Smart-living applications.

- Seismology: Analysis of earthquakes catalogs for hazard assessment

- Environment: Design of energy efficient buildings, groundwater flows, basin compaction
- Additive manufacturing.

ICAR

- **Processing and analysis of biomedical images:** bioinformatics and computational biology (analysis and integration of data from high throughput sequencing experiments, microscopy, and spectrometry); high throughput screening of stem cells in microscopy images; segmentation of melanomas in dermoscopic images; moving object detection for video surveillance and for characterizing the vitality of treated cells in electron microscopy videos.

- **Optimization for Machine Learning:** optimization techniques, such as Support vector machine and bundle methods for nonsmooth minimization problems, play a relevant role in Machine Learning (ML), since most ML problems are formulated as mathematical programming problems, and need the employment of efficient and specialized optimization algorithms.

  Multiple Instance Learning (MIL): the objective is to categorize bags of points (instances). Differently from supervised classification problems, where the label of each point in the training set is known, in a MIL problem only the labels of the bags are known, whereas the labels of the instances are unknown. Different mathematical programming models have been proposed such as mixed integer nonlinear programming models and a nonconvex nonsmooth unconstrained optimization ones.

- **Non-smooth optimization:** Wireless Sensor Coverage problem, non-smooth optimization for wireless sensor networks.

- **Transportation and logistics:** Optimization models for planning of urban transit accounting for guide automation, high quality user preferences, and multimodal integration; Optimization models for the management of multimodal container terminals account for zero-inventory logistics.

IIT

Models and algorithms for the solution of complex problems arising in some topical applicative areas, such as **Web Information Retrieval** (Biological sequences and networks analysis/classification; Diseases classification and gene expression profiling), algorithmic for **Wireless Networks and Smart Mobility** (Car Sharing, smart intersections, self-driving vehicles).

ISTI

- Applications to **structural health monitoring of historical masonry buildings** and their dynamic identification.

- **Computer Vision** and **Computer Graphics** applications: 3D shape analysis in digital anthropometry, for the development of health monitoring systems, 3D Digital Fabrication, environmental sensor monitoring.

  The applications include the virtual restoration and inpainting of degraded manuscript images.

  Applications were carried out in **brain research** (sleep, consciousness).

INM

- **Marine hydrodynamics applications:** energy dissipation of marine flows characterized by breaking waves and high free-surface deformations.

  A new hybrid Lagrangian-Eulerian approaches have been devised: in these schemes the standard mesh-based solvers have been coupled to particle methods in order to retain the advantages of both approaches and tackle complex problems of involving vorticity generation and free-surface deformation.
Another class of particle methods, the Diffused Vortex Hydrodynamics, has been developed and validated for simulating flows around complex bodies at intermediate Reynolds numbers, with specific focus on the wake generated past bodies.

4. EMERGING RESEARCH CHALLENGES

- Modelling and simulation of:
  natural phenomena, competitive species and biological invasions, engineering processes across large ranges of scales (combining stochastic and deterministic approach, new computational methods and tools);
  life cycle of industrial products and systems for new solutions/services (combining physics-based modelling with data-based one).
  - Stochastic geometric mechanics.
  - Biomathematics for new implementations and new applications.
  - Getting the most from increasing amount of data in health, mechanics and industry, economics, environment (inverse problems).
  - Decision making under risk/uncertainty in crime prevention, climate change, migration and defence (efficient algorithms, optimization of big data sets).
  - Image data manipulation (quantitative analysis).
  - Real-time monitoring of data stream (data reduction, handling of different sources/forms of data).
  - Complex and CPU-time consuming measurement processes (validation, verification, uncertainty estimate).

5. CONCLUSIONS

Mathematics is recognized today as essential and indispensable for addressing the major challenges in science, technology and society.

The envisaged changes in key technologies for present and future HPC systems will have significant impact on the development of scientific computing applications. New mathematical methods, numerical analysis, algorithms and software engineering for extreme parallelism are being addressed in order to take real advantage from the new systems as it is stressed in the European Technology Platform for HPC (ETP4HPC) Strategic Research Agenda.

Faced with the growing wealth of data on social, technical, environmental, economic, ecological, and technological systems, new and sophisticated mathematical tools are required for these data to help us tackle pressing societal challenges, provide us with the necessary technological advantages and approach new and further frontiers of knowledge.

It is worth noticing that current developments in big data analysis and HPC’s mathematical basis have shown that even existing areas of mathematics formerly deemed merely theoretical, such as algebra and topology, are now very important for these fields. Similarly it is impossible to predict now what mathematical areas should be in the focus, as well being exploitable in 50 years.

Mathematicians will be essential for identifying the potential of emerging and existing mathematical fields, amongst other areas, for the development of exascale and quantum computing, analytical and simulation tools to meet the future environmental, societal and industrial challenges.

Quite importantly, the need for collaboration and increasing convergence between different mathematical disciplines as well as between mathematics and other sciences is definitely evident.
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### PROJECT AREA 1: DEVICES AND SYSTEMS FOR ICT

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## PROJECT AREA 3: DATA, CONTENT AND MEDIA

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## PROJECT AREA 9: BIOTECHNOLOGY

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**PROJECT AREA 11: TECHNOLOGIES FOR THE USE AND PRESERVATION OF CULTURAL HERITAGE**

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