WHITE PAPER AP6
ROBOTICS AND CONTROL SYSTEMS

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)[1] 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

[1] HORIZON 2020. (2016). Robotics 2020 Multi-Annual Roadmap For Robotics in Europe. https://www.eu-robotics.net/cms/upload/topic_groups/H2020_Robotics_Multi-Annual_Roadmap_ICT-2017B.pdf. Accessed May 30, 2018.

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 ***percetion 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.

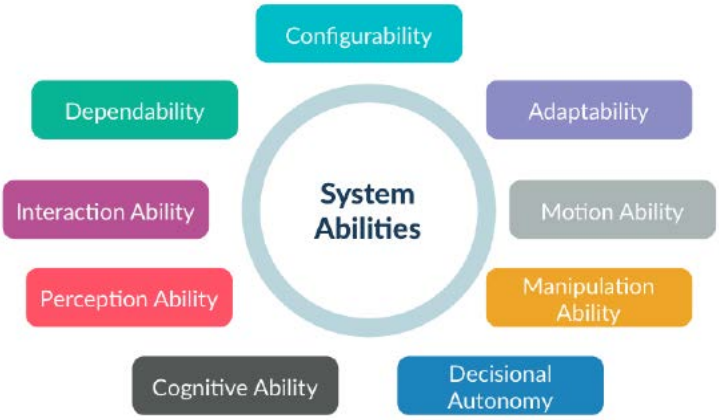

Figure 1 Robot system abilities as defined by the Horizon 2020 Multi-Annual Roadmap for Robotics (MAR) in Europe.

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.[2]

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.

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

[2] Thierry Peynot, Sildomar Monteiro, Alonzo Kelly, Michel Devy, Editorial: Special issue on Alternative Sensing Techniques for Robot Perception, Journal of Field Robotics 32(1), 1–2 (2015).

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[3] 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[4,5]. 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[6]. Intelligent robots require model-based autonomy solutions[7] 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[8]. 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.,

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[3] Villagrossi, E., Pedrocchi, N., Beschi, M., Molinari Tosatti, L.. (2018), A human mimicking control strategy for robotic deburring of hard materials, International Journal of Computer Integrated Manufacturing, ISSN: 0951-192X, DOI: 10.1080/0951192X.2018.1447688
[4] Thrun, S., & Mitchell, T. (1995). Lifelong robot learning. Robotics and autonomous system, 15, 25-46
[5] Weng, J., McClelland, J., Pentland, A., Sporns, O., Stockman, I., Sur, M. & Thelen, E. (2001). Autonomous mental development by robots and animals. Science, 291, 599-600.
[6] Baldassarre, G., & Mirolli, M. (Eds.) (2013). Intrinsically motivated learning in natural and artificial systems. Berlin: Springer-Verlag.
[7] Félix Ingrand, Malik Ghallab. (2017). Deliberation for autonomous robots: A survey. Artificial Intelligence. Volume 247. Pages 10-44. ISSN 0004-3702.
[8] Bruno Siciliano, Oussama Khatib. (2016). Handbook of Robotics. Chapter 14 “AI Reasoning Methods for Robotics”. Springer. Pages 329-356. ISBN 978-3-319-32552-1.

swarms)[9,10]. The main challenge here is the design of robust and scalable decentralized systems with predictable dynamics, which include both spatial and temporal constraints[11,12,13]. 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[14]. 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.

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[9] Brambilla, M., Ferrante, E., Birattari, M., & Dorigo, M. (2013). Swarm robotics: a review from the swarm engineering perspective. Swarm Intelligence, 7(1), 1–41. http://doi.org/10.1007/s11721-012-0075-2

[10] Chen, I.-M., & YIM, M. (2016). Modular Robots. In B. Siciliano & O. Khatib (Eds.), Springer Handbook of Robotics (Vol. 24, pp. 531–542). Cham: Springer International Publishing. http://doi.org/10.1007/978-3-319-32552-1_22

[11] Korsah, G. A., Stentz, A., & Dias, M. B. (2013). A comprehensive taxonomy for multi-robot task allocation. The International Journal of Robotics Research, 32(12), 1495–1512. http://doi.org/10.1177/0278364913496484

[12] Nunes, E., Manner, M., Mitiche, H., & Gini, M. (2017). A taxonomy for task allocation problems with temporal and ordering constraints. Robotics and Autonomous Systems, 90 IS -, 55–70. http://doi.org/10.1016/j.robot.2016.10.008

[13] Reina, A., Valentini, G., Fernández-Oto, C., Dorigo, M., & Trianni, V. (2015). A Design Pattern for Decentralised Decision Making. PLoS ONE, 10(10), e0140950–18. http://doi.org/10.1371/journal.pone.0140950

[14] The Impact of Control Technology, 2nd ed., T. Samad and A.M. Annaswamy (eds.), 2014. Available at www.ieeecss.org

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[15]. 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[16].
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[17, 18].
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[19]. The application of the IoT paradigm in a wider context has been investigated and possible technology enablers, from both already available and upcoming standards, have been surveyed[20]. A dedicated service-oriented approach, enabled by high-speed in-vehicle networks, has been devised to manage automated working machines[21].

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

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[15] Reina G., Milella A., Galati R. (2017) *Terrain assessment for precision agriculture using vehicle dynamic modelling*, Biosystems Engineering, Volume 162, October 2017, Pages 124-139.
[16] Reina G., Milella A., Rouveure R., Nielsen M., Worst R., and Blas M.R. (2016) *Ambient awareness for agricultural robotic vehicles*, Biosystems Engineering, Volume 146, Pages 114–132, ISSN: 1537-5110
[17] Petitti A., Di Paola D., Milella A., Lorusso A., Colella R., Attolico G., and Caccia M. (2016) *A Network of Stationary Sensors and Mobile Robots for Distributed Ambient Intelligence*, IEEE Intelligent Systems, Volume: 31, Issue: 6, Page(s): 28 – 34, ISSN: 1541-1672.
[18] Scilimati V., Petitti A., Boccadoro P., Colella R., Di Paola D., Milella A., Grieco L.A. (2017) *Industrial Internet of Things at work: a case study analysis in Robotic-aided environmental monitoring*, IET Wireless Sensor Systems, DOI: 10.1049/iet-wss.2017.0032 , Online ISSN 2043-6394 Available online: 21 June 2017.
[19] Bacco, F.M., Berton, A., Ferro, E., Gennaro, C., Gotta, A., Matteoli, S., Paonessa, F., Ruggeri, M., Virone, 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)
[20] Dariz, L., Selvatici, M., Ruggeri, M., Costantino, G., Martinelli, F., "Trade-Off Analysis of Safety and Security in CAN bus communication", IEEE International Conference on Models and Technologies for Intelligent Transportation Systems, 26-28 June 2017, Naples (Italy)
[21] Malaguti, G., Ruggeri, M., Dariz, L., and Selvatici, M., "In-Tractor Cloud: A Vision of Service-Oriented System Design Enabled by High-Speed In-Vehicle Networks for a Safer Task and Machine Management", SAE Technical Paper 2016-01-8130, 2016, https://doi.org/10.4271/2016-01-8130.

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[22]. Reinforced random walks have been proposed for wide-area exploration and exploitation of resources, achieving high efficiency, robustness and scalability[23].
Pioneering contributions have been given to the theoretical foundation of the open-ended learning robot field[24], and to early models based on bio-inspired solutions.[25] 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.[26, 27]
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-base planning entails the control over time of different logical/physical components and temporal their behaviors

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[22] Reina, A., Valentini, G., Fernández-Oto, C., Dorigo, M., & Trianni, V. (2015). A Design Pattern for Decentralised Decision Making. PLoS ONE, 10(10), e0140950–18. http://doi.org/10.1371/journal.pone.0140950

[23] Albani, D., Nardi, D., & Trianni, V. (2017). Field coverage and weed mapping by UAV swarms (pp. 4319–4325). Presented at the 2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS, IEEE. http://doi.org/10.1109/IROS.2017.8206296

[24] 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.

[25] Fiore, V. G., Sperati, V., Mannella, F., Mirolli, M., Gurney, K., Firston, K., Dolan, R. J., & Baldassarre, G. (2014). Keep focussing: striatal dopamine multiple functions resolved in a single mechanism tested in a simulated humanoid robot. Frontiers in Psychology, 5, e1-17.

[26] Santucci, V. G.; Baldassarre, G. & Mirolli, M. (2016). GRAIL: a Goal-Discovering Robotic Architecture for Intrinsically-Motivated Learning. IEEE Transactions on Cognitive and Developmental Systems, 8, 214-231.

[27] Seepanomwan, K., Santucci, V. G., & Baldassarre, G. (2017). Intrinsically Motivated Discovered Outcomes Boost User's Goals Achievement in a Humanoid Robot. The Seventh Joint IEEE International Conference on Development and Learning and on Epigenetic Robotics (ICDL-EpiRob2017), 178-183

(i.e., the timelines) for guaranteeing the achievement of desired goals.[28,29] The integration of such technology with Verification and Validation solutions[30] is fostering also robust control solutions for guaranteeing effectiveness and safety of autonomous robots[31].
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, 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

[28] Cialdea Mayer M., Orlandini A., Umbrico A. (2016). Planning and execution with flexible timelines: a formal account. Acta Informatica.
[29] Umbrico A., Cesta A., Cialdea Mayer M., Orlandini A. (2017) PLATINUm: A New Framework for Planning and Acting. AI*IA 2017 Advances in Artificial Intelligence. AI*IA 2017. Lecture Notes in Computer Science, vol 10640. Springer.
[30] Bensalem, S., Havelund, K., Orlandini, A. (2014). Verification and validation meet planning and scheduling. International Journal on Software Tools for Technology Transfer, 16 (1), pp. 1-12. Springer.
[31] Cesta, A., Finzi, A., Fratini, S., Orlandini, A., Tronci, E. (2010). Analyzing flexible timeline-based plans. In Proc. of European Conference on Artificial Intelligence (ECAI). Frontiers in Artificial Intelligence and Applications, 215, pp. 471-476. IOS Press.

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[32].
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

[32] Pellegrinelli, S., Orlandini, A., Pedrocchi, N., Umbrico, A., Tolio, T. (2017). Motion planning and scheduling for human and industrial-robot collaboration. CIRP Annals - Manufacturing Technology. 66 (1). pp. 1-4. Elsevier.ope

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 benefiting 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 are 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.

PROJECT AREA 6: ROBOTICS AND CONTROL SYSTEMS

Editorial team and Contact person (CP)	Institute	Email
BALDASSARRE GIANLUCA	ISTC	gianluca.baldassarre@istc.cnr.it
BRUSAFERRI ALESSANDRO	STIIMA	alessandro.brusaferri@itia.cnr.it
CARRAVETTA FRANCESCO	IASI	francesco.carravetta@iasi.cnr.it
CESTA AMEDEO	ISTC	amedeo.cesta@istc.cnr.it
DABBENE FABRIZIO	IEIIT	fabrizio.dabbene@ieiit.cnr.it
GAGGERO MAURO	INM	mauro.gaggero@ge.issia.cnr.it
INFANTINO IGNAZIO	ICAR	ignazio.infantino@icar.cnr.it
LAGALA FRANCESCO	INM	francesco.lagala@cnr.it
LUCHETTA ADRIANO	IGI	adriano.luchetta@igi.cnr.it
MANISCALCO UMBERTO	ICAR	umberto.maniscalco@icar.cnr.it
MARTELLI MASSIMO	IMAMOTER	m.martelli@imamoter.cnr.it
MILELLA ANNALISA (**CP**)	ISSIA	milella@ba.issia.cnr.it
MOLINARI TOSATTI LORENZO (**CP**)	STIIMA	lorenzo.molinaritosatti@itia.cnr.it
PALUMBO PASQUALE	IASI	pasquale.palumbo@iasi.cnr.it
PEDROCCHI NICOLA	STIIMA	nicola.pedrocci@stiima.cnr.it
ROSSI FRANCESCA	IFAC	f.rossi@ifac.cnr.it
TRIANNI VITO	ISTC	vito.trianni@istc.cnr.it
VERUGGIO GIANMARCO	IEIIT	gianmarco.veruggio@ieiit.cnr.it
VICENTINI FEDERICO	STIIMA	federico.vicentini@itia.cnr.it