eu ROBIN STRATEGIC RESEARCH AGENDA

EXECUTIVE SUMMARY

THE EUROPEAN EXCELLENCE NETWORK ON AI-POWERED ROBOTICS

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Robotics has achieved remarkable progress over the last two decades, progressively expanding its reach beyond industrial automation that was its first major application. The work of hundreds of research groups worldwide has led to **robots that are significantly more autonomous, smarter, lighter, more robust, and less costly than the first generation of industrial robots**. This was made possible by the development of new families of control algorithms, the growth in available computing power and miniaturization of electronic components and batteries, the development of new sensors and the integration of their data in the control of robots, the evolution of mechatronics and the experimentation with new soft materials components that have expanded the palette of robotic hardware.

The continuous advancement of these research trends is now converging with the fast-paced evolution of artificial intelligence techniques and leading to **embodied AI**, i.e. artificial intelligence that is integrated into physical bodies that interact with the environment, with other intelligent agents and with humans. This allows robots to leave the security of the industrial world and handle the uncertainty and complexity of human-inhabited environments to perform tasks that cannot be fully described mathematically in advance.

As a result, a new generation of complex, cognitive and **adaptive multi-purpose machines is within reach**. These robots will differ from previous ones because of their ability to **learn new tasks from humans, from other robots and from the environment**, to interact safely and effectively with humans, and to operate with agility in unstructured settings – either natural or man-made, but not a priori designed for robots.

ROBOTICS ACHIEVEMENTS IN THE LAST DECADES

Research on **manipulators**, historically the first large family of robots, saw significant achievements in the last 20-30 years. Robots can manipulate and grasp objects with different shapes, positions and trajectories. Compliant control allows them to be guided by the forces applied on them rather than being programmed to reach predefined positions, thus adjusting to contact with objects or humans. Steady progresses have been made in the design of new materials that led to several prototypes, including a few commercial products, of **soft grippers and soft robotic hands for manipulating non-rigid objects**, and proofs of concept of soft actuators - fluidic, pneumatic, or based on functional materials such as shape-memory alloys. In the medical field, researchers showed that it is feasible to harness neural or muscular signals to control prosthetic limbs. In addition, digital twins of large environments enable robot programming at a more abstract level and facilitate the realization of robotics tasks of greater complexity, for example in production lines.

Transfer of these and other technologies to the commercial domain has resulted in industrial robots that can tackle increasingly complex tasks. A key advancement has been the introduction of **collaborative robots** (co-bots) that have expanded automation to less structured industry environments. Several robotic hands and grippers are on the market, for manipulating and grasping different categories of rigid objects. **Surgical robotics** has grown since the early 2000s into **one of the main markets for service robotics**, and many European start-ups are now leveraging miniaturization, machine learning and soft components to lower prices and expand use-cases. **Robotic arms** operate on **spacecrafts** and **autonomous rovers**, demonstrating robustness in an extremely challenging environment.

The mechanical design and control of **autonomous vehicles**, from cars and drones to walking and swimming robots, to enable navigation in different environments has improved thanks to sensors such as compact IMUs (Inertial Measurement Units), compact cameras, compact LiDAR, and to the use of machine learning. **Visual SLAM** (Simultaneous Localization and Mapping) is now a **mature technology** that allows mobile robots to explore an unknown environment while building a map of it. **Legged robots can now locomote** on regular or moderately irregular terrains. **Humanoids** have become more agile and can bend down to pick up objects on the floor and **walk while carrying objects in conjunction with humans** or other robots. Aerial robots have robust flight capabilities and various degrees of autonomy, including autonomous flight at high-speed relying on cameras when in controlled light conditions. **Drones with manipulation capabilities** have been developed and tested, bridging the gap between the two traditionally separate areas of robotics. **Underwater robotics** offers a wealth of solutions, from small robot fishes to larger machines that **can explore the depth of oceans**. A few prototypes of autonomous cranes and other large machines for construction have been deployed.

Advancements in autonomous navigation have resulted in the **commercial success of robotic vacuum** cleaners (now the largest share of marketed commercial robots), **lawn mowers and pool cleaners**. Partially or totally autonomous **drones** are now being deployed for **surveillance, monitoring, defense, inspection, and maintenance**. The ongoing real-world tests of driverless cars are also a result of decades of research on autonomous navigation. Wheeled robots are used in logistics and warehouse management, and mobile robots of various types are applied to search and rescue and disaster management. Finally, wheeled and tracked rovers have been sent to explore bodies of the solar system.

SHORT-TERM RESEARCH ROADMAP

There are many "**low-hanging fruits**" that research can grasp within the next 5-7 years – backed by solid science, and that can be deployed in the real world with focused technology transfer efforts. First and foremost, the new generation of robots deployed in factories and beyond will be endowed with the ability to learn through continuous interactions with humans, the environment, and even from other robots. Equipped with the necessary knowledge to operate in the real world, robots will have a certain level of understanding of the world that surrounds them and be capable of interpreting its dynamics in real time and reason about it. Robots will be endowed with faster control capabilities for real-time planning and robust execution of actions capable of safely handling unexpected contacts and disturbances. Last but not least, new bodies and hardware components enabling robots to act and perceive the world as humans, and to become more efficient, will open new avenues for the deployments of robots. The key ingredients to achieve this are multi-faceted. We divide them here in four major categories.

LEARNING

AI systems such as foundation models can be leveraged to help generate plans and actions for new environments and tasks previously not encountered. They can also be applied to improve the recognition of objects and their affordance in manipulation tasks, or to improve scene recognition during navigation in unknown environments. AI can improve state estimation and control of soft robots, and AI algorithms can be designed to specifically address bilateral physical communication with humans with natural language and gestures.

LEARNING

- Foundation models for new environments and new tasks
- Improved object and scene recognition
- AI for state estimation of soft robots

REASONING

- Physics simulations
- Programming tools
- Digital twins

CONTROL

- New modelling and control solutions
- Aerial manipulation
- Gesture and speech recognition
- Plug-and-play solutions for co-bots

HARDWARE

- More versatile grippers
- Teleoperation stations
- Modular, self-configuring components
- Arms and grippers for drones

SHORT-TERM RESEARCH ROADMAP

REASONING

Physics simulations and visual rendering can be transferred from virtual reality and game technologies to robot applications, providing better simulation methods tailored for the motions of robot bodies. More powerful tools can be introduced for programming robots for specific application domains, with built-in intelligence that facilitate the composition of robot programs by specializing and combining software component templates. **Digital twins** of large man-made and natural environments (including factories) can be developed to enable **robot programming at a more abstract level** and facilitate the realization of robotics tasks of much larger complexity, including in entire production lines.

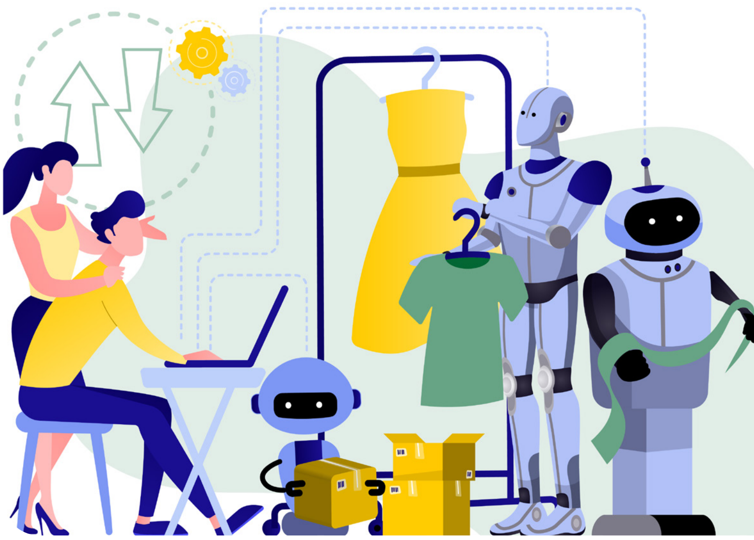
CONTROL

As robot bodies become more complex, new solutions are available to extend the methodical basis for modeling and controlling them, such as **geometric mechanics and dynamics, differential geometry, and algebraic topology**.

At the same time, **machine learning** will play an increasing role in robotics, especially **for systems for which physical models are lacking or are not accurate**. The trade-off between model-based control and machine learning is one of the main challenges of future robot control. Control of flying robots can be enhanced to combine stable flight with manipulation, including on-board real-time perception and planning. Gesture and speech recognition as well as AI-based body interfaces can be applied on a larger scale to give commands to robots. Co-bots can benefit from increased customization and more plug-and-play solutions that will make it easier for end users to adapt them to different tasks. Improved interaction between humans and soft robots is going to be another medium-term research focus, including wearable devices capable of real-time state estimation of the body thanks to soft sensors.

HARDWARE

More versatile grippers to tackle multidisciplinary grasping can be obtained through novel designs, and by co-designing grippers and their software, and with the addition of 3D **tactile sensors** to manipulate smaller deformable objects such as fruits, vegetables, garments. **Teleoperation** stations, supported by **5G/6G high bandwidth communication**, can allow operators to control a robotic avatar over any distance with feedback of interaction forces. Steps can be taken towards new modular components with standard protocols that autoconfigure as part of a bigger and complex robotics system like it is now the case for computer add-ons. Flying platforms can be equipped with robotic arms and grippers for aerial manipulation, with increased force and enhanced manipulation capabilities, to be used for inspection and maintenance of bridges, power lines, and high-rise buildings. Swimming and amphibious robots, which today are less advanced than legged and winged ones, can be improved and be applied for inspection of fish farms, submarine cables, and underwater platforms. A breakthrough towards real-life applications in legged humanoids can be expected.



WHERE WE'RE HEADING: LONG TERM ROADMAP

Looking beyond the next decade, there are still key scientific and technical challenges that robotics research must address before robots can perceive robustly, act ethically, reason abstractly, interact safely with humans, and cope with the high uncertainty of physical interactions in the real world.

LEARNING

Future robots will need **lifelong learning**, i.e. the ability to acquire new knowledge and learn new tasks along their operational life, instead of relying on an initial training dataset that could never prepare them for the complexity and variety of the real world. This requires new paradigms based on incremental learning and able to convert input-output learning to structured knowledge, combining the power of learning with the paradigms of expert systems. In addition, they will need **transferable learning**: human intelligence relies on the ability to apply the knowledge acquired in one domain to new domains - thus solving new problems and facing unexpected situations – and to share knowledge among individuals. Similarly, robots need analytic and data-driven methods for learning skills from human demonstrations, transferring learned skills to novel tasks or different robots and environments, transferring skills learned in simulation to real robots, transferring learned perception routines between robots.

LEARNING
- Lifelong learning
- Transferable learning

REASONING
- Generalized robot programs that automatically specialize themselves for different situations and tasks
- Representations of intended actions and their consequences

CONTROL
- Mathematical models of soft systems
- Multimodal locomotion
- Multi-robot systems
- Intuitive human-robot interaction based on natural language

HARDWARE
- Artificial muscles
- Tactile robotic skins
- Neuromorphic computing
- Distributed power generation
- Morphological computation

LONG-TERM ROADMAP

REASONING

Research must aim for generalized robot control programs that automatically specialize themselves for different objects, tools, purposes, and situation contexts through generalized knowledge representation and reasoning; that can construct representations of the actions that they intend to perform, and reason about them to forestall unwanted side effects. This will allow robots to automatically deploy themselves in their operating environments, reason about the consequences of their actions, dynamically adjust their course of action to the demands of humans, self-diagnose when they are not understanding the situation and give appropriate feedback so that humans can take over. In a nutshell, robots that understand what they are doing.

CONTROL

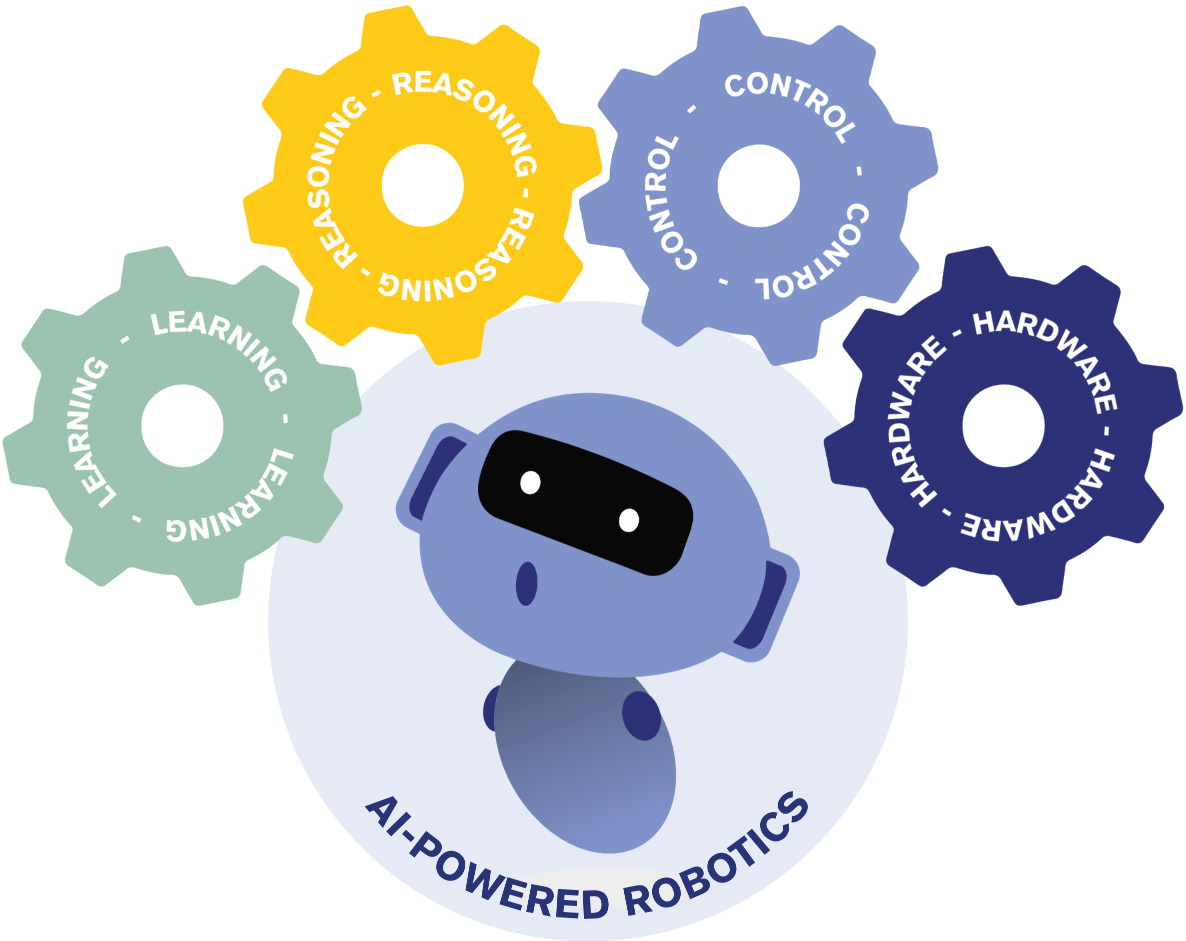
The mathematical modeling of soft systems must be improved, to effectively control soft robots and their interactions with deformable objects. **Multimodal locomotion** control is needed to allow legged or amphibious robots to change modes of locomotion, switching from walking to jumping, climbing, squeezing through narrow passages – including not only efficient control of each different gait but also, crucially, autonomous decision on when to switch gait. Significant improvements are needed on control of multi-robot systems where several robots of different types co-operate on tasks, including control of robotics swarms with several tens, or even hundreds, of individuals: here, progress will be required on creating **shared representations** of the environment (that different robots may observe from varying points of view and with different sensors) as well as on common operative systems and communication protocols. **Safe and intuitive human-robot interaction** for non-expert users must be achieved, including two-way communication with robots based on natural language and control/perception skills that permit close physical interaction for physical rehabilitation and elderly care.

HARDWARE

If robots are to approximate the versatility of living beings in facing tasks and environments, they need to replace at least some of their current electromechanics actuators with **artificial muscles** that have sufficient power output, are modular and **self-healing**. They also need flexible, robust, self-healing tactile skins, with high spatial resolution and force direction sensing to allow effective interaction with objects as well as safe interaction with humans. This also implies AI systems to process tactile sensing data locally at the point of contact (i.e. **edge AI**), to reduce the quantity of data to be processed by the central processing unit.

New sensors that can be integrated in robots include ultra-low latency vision sensors, ultra-wide band localization, 3D force sensors, proximity sensing, sensors for human physiology. **Neuromorphic computing** is needed to overcome classic computing architectures and classical communication theory, to increase performance and energy efficiency of robot electronics under the continuously increasing demand for computation and communication power.

Improved energy efficiency of onboard computation is needed to increase autonomy and operational life. For humanoids in particular this may require having distributed power generation along the body of the robot, instead of a backpack, which in turn will require novel materials science contribution. Ultimately, improved **energy efficiency** can be achieved through morphological computation, i.e. designing the robot's soft body and generally the intrinsic body dynamics so that its shape and modes of deformation constrain its movement, reducing the need for computation and control of its states.



CONCLUSION

Ultimately, robotics has the potential to contribute to many of the United Nations' industry and **environment-related Sustainable Development Goals**.

Realizing this vision will require sustained investments in fundamental research and technology transfer, interdisciplinary collaboration with fields as diverse as computer science, materials science, and neuroscience, and a close interaction between academia and industry. **Europe has a vantage position in robotics**, and it will be crucial that it retains and strengthens the whole value chain, from design to manufacturing, without repeating past mistakes that have led to dependance for critical technologies (i.e. microchips). A balanced approach to AI development requires investing not only in algorithms, but also in the ecosystems in which they will operate and in the underlying technologies.

Technological development must be accompanied by research on the **social, psychological and legal dimensions of the relationship between humans and robots**, to understand how humans can develop trust - while avoiding excessive trust - in robots, and how attitudes to robots change in time and across different cultures. This will ensure that future advancements in AI-based robotics work in the interest of sustainable development, equality and social justice.

ROBOTS AND SUSTAINABLE DEVELOPMENT

The next generation of AI-powered robots can help tackle key challenges faced by our societies.

An aging population: the need for assistance to the elderly and disabled in homes, or the need for physical and cognitive rehabilitation after incidents and diseases, will greatly increase in the next decades, with simply not enough human caregivers.

Humanitarian responses during natural and man-made disasters that are predicted to become more frequent because of global warming, pollution and international crises. Robots will be increasingly needed for search and rescue, or for environmental remediation and decommissioning of industrial sites, including nuclear plants, and inspection of infrastructures after the disaster.

The transition towards sustainable growth and a circular economy: robots can contribute to economic growth by increasing productivity in sectors that have not been automated so far, such as the textile or food industry, high-mix low-volume manufacturing, and maintenance of the European industrial and civil aging infrastructures. At the same time they can address the circular economy's increasing need to sort, recycle, and recover products and materials and keep them in the production cycle, including the handling of electronic components, batteries and toxic materials that should not be performed by humans.

Climate change mitigation: robots for environmental monitoring can contribute to a more precise assessment of the effects of climate change. Drones monitoring fields, mobile robots applying water and pesticides, robots picking and handling produce can help agriculture adapt to climate change, while relieving humans of some of the heaviest tasks and reducing food waste thanks to more efficient storing and transport.

AI AND ROBOTICS

From automatic translation to image recognition, from systems mastering complex board games to ChatGPT and the other language models, deep learning has achieved a lot in the last decade, and expectations on future developments of AI could not be higher.

Robotics has greatly benefitted from advancements in machine learning: for example, locomotion in legged robots has advanced greatly thanks to reinforcement learning, that allows to define a high-level target such as the speed of locomotion or a destination without a full mathematical description of the problem. Thanks to the progress in deep learning, driverless cars are being tested as a commercial service in major cities. Robot simulators have advanced thanks to deep reinforcement learning, which allows exploring policies with different environmental conditions in a reasonable amount of time before trying them on the actual robot.

But unlike language models and image recognition algorithms that only deal with bits, **embodied AI** poses specific challenges. Robots cannot rely on huge datasets that can be digested in relatively short times. Datasets themselves based on physical interactions (locomotion on different terrains or grasping of various objects) are simply not available and cannot be quickly assembled: having robots execute tasks in the real world takes time, and risks damaging the robot or its environment when attempts go wrong. A training dataset for flying robots, for example, would need to be impossibly huge, since drones can fly at vastly different altitudes and tilting positions with respect to the ground. The use of simulators is of great help, but for many tasks sim-to-real transfer is still a challenge.

Another crucial difference with non-embodied AI is that robots often perform safety-critical applications, and safety agencies would not approve a robot powered by an AI without enough transparency on when and why it may fail.

For this reason, AI-powered robotics will most likely include deep learning in combination with models that incorporate fundamental knowledge about the world and use it to guide and constrain the use of learned policies.

Ultimately, because no dataset or simulation can live up to the complexity of real-world physical interaction, robots will require **lifelong learning** and **transferability of knowledge** across tasks, across robot bodies and across environments, as well as between humans and robots. Research will need to focus on understanding what to transfer (identifying relevant knowledge about environments, objects, and tasks constraints); how to transfer (formalizing prior knowledge on robot bodies and sensors, kinematics and dynamics, and for a given task/environment/body find feasible sets of motor commands); and when to transfer (learning to recognize similarities across environments, objects, and tasks constraints).

HUMAN-CENTERED ROBOTICS

Future robots - be they humanoids, drones, legged robots, manipulators, or entirely new soft robots - are expected to operate in much **closer contact with humans**, collaborating and interacting with them in homes and offices as well as in public spaces. Ultimately, the vision of **AI-powered robotics** is to enable humans and robots to share spaces and tasks, deciding and acting together, while **preserving humans' privacy and autonomy**. This creates several new challenges. On the technical side, we need to devise and build cognitive and interactive abilities that allow **pertinent, transparent, and legible** behaviours in robots, a necessary premise to ensure that they can be trusted to work in collaboration with humans. On the safety side, we need to evolve current **safety standards** so that they account for the use of robots not only in private, controlled spaces but also in public, crowded ones: robots must be able to account for the heterogeneity of pedestrians, the dynamics of crowds, for social norms, and for real people's disorderly and at times mischievous behavior.

Many future use cases – from autonomous vehicles to prostheses and exoskeletons in the medical field – imply shared-control systems where humans delegate part of the decision-making and control functions to artificial agents. This creates the additional challenge of how to ascribe **responsibility for failures** and potential damages. A clear **regulatory** and **ethical** framework is needed, one with human needs and values firmly at its center.

It is only through tight coordination with human-centered disciplines such as ethics, psychology, social sciences, that robotics can deal with the social, societal and ethical issues related to the use of autonomous machines in professional, public and domestic environments.