Lernende Systeme
GERMANY'S PLATFORM FOR ARTIFICIAL INTELLIGENCE

AI in Robotics

White Paper

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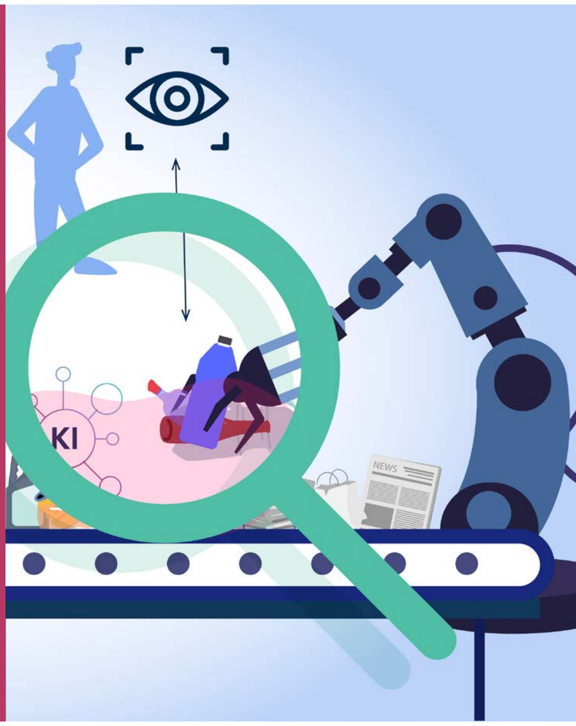
Working Group Learning Robotic Systems



Executive Summary

The ability to easily and intuitively adapt robotic systems to people, new tasks, and contexts is crucial to unlocking the potential of this technology in addressing the pressing challenges of our time. This includes, for example, maintaining and enhancing competitiveness, achieving technological sovereignty, managing demographic change, and building a circular economy. The rapid developments in machine learning in recent years, the decreasing costs of robots and components, and the increasing computing power are creating an optimistic spirit of innovation in the field of robotics. As a result, it will increasingly be possible to realize human-centered and adaptive robotics applications in social environments that were previously difficult or impossible to implement, such as in the service sector, skilled trades, daily life or healthcare. Nevertheless, it is essential to address safety-related challenges that accompany the development of this technology. Despite its potential for both the economy and society and despite technological advancements, the development of safe and reliable robots remains a central concern, as does the issue of cost-effectiveness.

Initial Situation

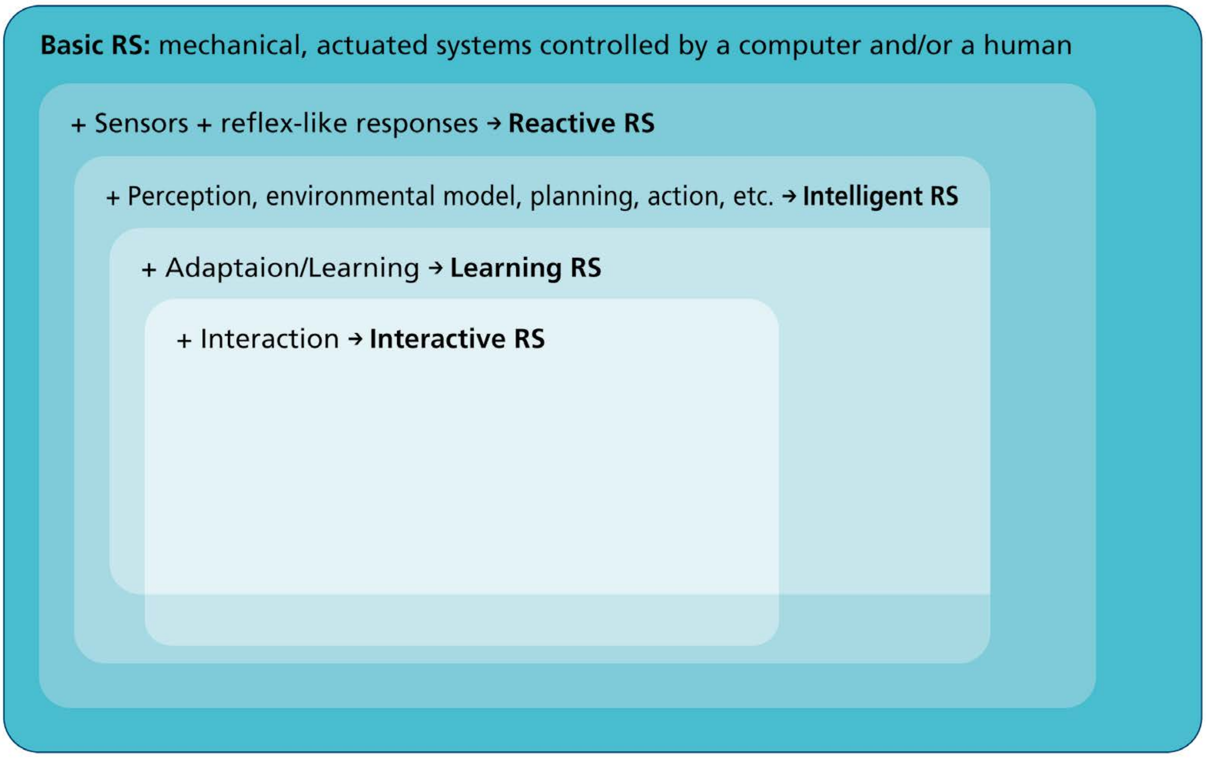
Technological progress and decreasing costs in the field of robotics suggest significant economic potential. The combination of AI methods with robotics is therefore seen as offering promising opportunities for development, enabling robots to become more flexible and adaptable to changing conditions, along with a growing market potential. Robots that can adapt to different tasks, people, and environments through interaction, thanks to easier operation and integration, require little expertise on the part of the users and reduce programming costs. This opens entirely new possibilities and can act as a lever to better exploit economic potential and tap into new business areas. With their wide range of cross-industry applications, robots are increasingly capable through the integration of AI technologies of navigating unstructured, dynamic environments and taking on more complex tasks, learning through interaction. In addition, robotics is regarded as a key technology for addressing societal challenges such as skilled labor shortages and sustainability goals. The concept of learning through interaction in robotics represents an important advancement. Interaction, simulation, and autonomy are increasingly being integrated, so that robots not only become intelligent systems, but can also continue to learn through interaction. This potential at the intersection of artificial intelligence and robotics must be harnessed and applied to tackle the challenges mentioned. Germany is generally well positioned in this regard but faces strong competition from Asia and the United States in both research and development and in practical applications of robotics. It is necessary to make strategic decisions today to avoid falling behind technologically and to seize the opportunities available to Germany and Europe.

To advance the development and practical application of this technology, three factors are required. First, motivation, which can stem from societal and economic challenges and associated goals. Second, the necessary capabilities such as technological know-how. And third, the right opportunities, which must be created through appropriate measures and a supportive legal, ethical, and social framework. This white paper focuses mainly on the technological foundations and their practical implementation. Non-technical aspects such as regulation and economic viability are mentioned but not discussed in detail.

Typology of Robotic Systems

To better understand the concept of learning and interactive robotic systems, the various types of robotic systems are first defined, based on the definition of robotics by Brady (1985), who described robotics as the intelligent connection of perception and action. To illustrate the gradual differences between robotic systems as their capabilities increase toward learning systems, a model is presented that categorizes robotic systems into successive types. Each subsequent type builds upon and includes the capabilities of the previous one. The individual types (basic, reactive, intelligent, learning, interactive) may also overlap to some extent and are therefore not always clearly distinguishable from one another.

Figure 1: **Robotic Systems (RS) – A graphical attempt at definition**



Source: concept and graphical overview based on Jürgen Beyerer.

Basic robotic systems are mechanical, actuated systems controlled by either a computer or a human. They can also be equipped with manipulators, such as grippers, and unlike automated machines, such as vending machines, they can be used for various purposes. Example: Industrial robots that perform precise, automated welding can be reprogrammed and equipped with different manipulators or tools to install car windows. This demonstrates multifunctionality.

Reactive robotic systems respond reflexively to specific situations based on predefined rules and use simple sensors. Example: A welding robot that begins working only when a workpiece passes through a light barrier.

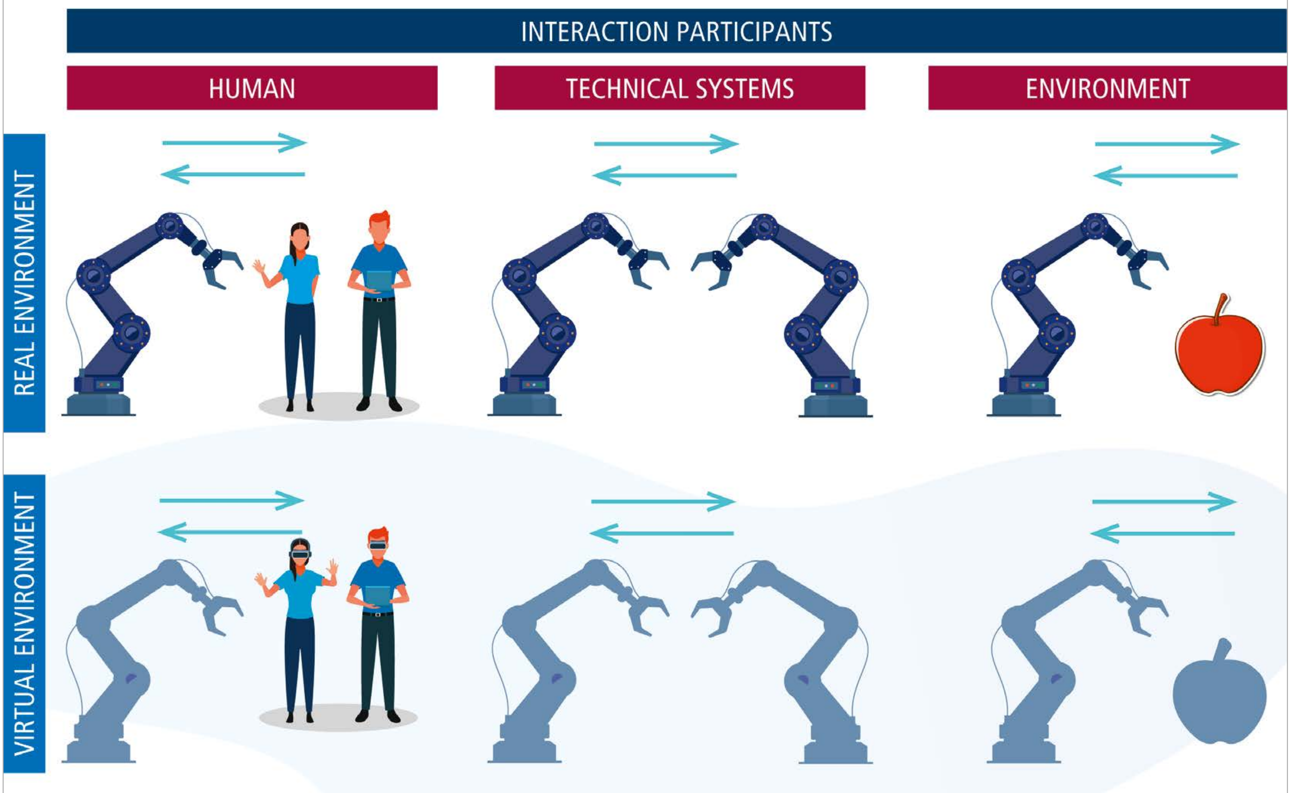
Intelligent robotic systems have advanced capabilities such as environmental and self-awareness, planning, modeling, and the execution of complex actions. Example: A mobile warehouse robot that independently identifies objects, sorts them correctly, or retrieves them upon request.

Learning robotic systems adapt to changes in their environment by acquiring new abilities during operation and optimizing existing ones through learning. In addition to the classic cycle of sense, understand, plan, and act, they incorporate the overarching meta-capability of learning. Example: Robots that improve their performance through experience, such as reinforcement learning during operation.

Interactive robotic systems are capable of actively engaging in their environment or with other agents. They can respond to actions and initiate their own. Example: Social or service robots that respond to human behavior and engage in mutual interactions.

Learning through interaction means that a robotic system generates new experiences, expands its capabilities, and improves its performance on a given task with respect to relevant quality criteria by interacting with people, other living beings, technical systems, or the environment, either in a real or simulated setting. Example: A robot observes a demonstrated action and then imitates it. Table 1 provides an overview of the various forms of learning through interaction. In addition to the different learning types, the temporal dimension also plays a role, as learning can occur in real time during interaction or at a later point, such as between different deployments.

Table 1: **Typology of Different Forms of Learning through Interaction**



		INTERACTION PARTICIPANTS		
		HUMAN	TECHNICAL SYSTEMS	ENVIRONMENT
ENVIRONMENT	REAL	The robot learns through observation and imitation, collaboration, and communication with the human.	The robot learns through observation and imitation, collaboration, communication, or data exchange with other robots.	The robot interacts with objects in a real environment.
	VIRTUAL	The robot learns through interaction with human(s) in a virtual environment.	Robots learn from interaction between virtual representations of the robots.	A virtual representation of a robot interacts with virtual objects.

Source: own illustration.

Use Cases

Seven application examples from different domains illustrate where and how interactive learning robots could provide support in the near and more distant future. These domains include medical technology, waste and recycling management, skilled trades, agriculture, space exploration, ocean conservation, and caregiving. Both the current state and future perspectives are examined.

The combined analysis of the seven application examples identifies both commonalities and differences. Two separate groups of use cases can be distinguished, each with specific characteristics. It becomes apparent that the robotic systems used in applications operating far from humans in unstructured and natural environments, such as maritime robotics and space robotics, share similar requirements. These include a higher degree of autonomy and the ability to log and process data directly on the robot. They also face similar challenges, such as limited access to computing power during operation. Parallels can also be observed among the use cases where robots operate closer to humans in more structured and human-shaped environments. This includes robotics in skilled trades, recycling and cultivating meadow orchards, assistive robotics in caregiving, and wearable robotics. Key requirements in these settings include datasets for robotic skills and safety concepts for interaction and communication with robots. The challenges involve concerns about being replaced by autonomous systems among domain experts or staff, as well as the integration of such systems into operational practice, including functional safety considerations.

In addition, there are cross-cutting synergies among the seven use cases from which multiple areas of robotics can benefit. Examples include learning methods such as reinforcement learning, self-supervised and continuously learning systems, supervised learning, and active learning. Learning sources include technologies like 3D cameras, multimodal sensors, data from virtual environments or simulations, and process or system data. Robots can also learn from various processes, including general human feedback, variable autonomy, remote control, and teleoperation.

In addition, comprehensive quality assurance is essential for the successful deployment of learning robotic systems. In the use cases, key approaches included human feedback, such as corrections, validations, and authorizations, along with the automatic evaluation of that feedback, and the exploration and verification of training data. Further measures include testing and assessing learned actions in real or virtual environments, statistically comparing actions with defined quality criteria, and using monitoring and safety systems. Systematic documentation using data recorders is also important for making the system's behaviour understandable and transparent.

The implementation of such learning robotic systems requires both technical and non-technical prerequisites. On the technical side, important factors include robust vision systems, multimodal sensors, real-time capability, virtual testing environments, the ability to learn from few examples (few-shot learning), and compliance with regulatory requirements. On the non-technical side, key factors include trust in the technology, willingness to interact with a robot, and the qualifications of the people involved. Both perspectives must be taken into account to ensure the successful practical deployment of learning and interactive robotic systems.

Key insights into interactive learning in robotic systems can be gained by examining various use cases and identifying overarching focus areas that are critical for successfully implementing these technologies. At the core is the interplay between technical prerequisites, such as high safety requirements, sufficient and relevant data, or specific technical requirements, and non-technical prerequisites, including complex authorisation processes, uncertainties regarding legal frameworks such as the General Data Protection Regulation (GDPR) or the AI Act, and economic feasibility. Additional focus areas include building trust in robotic systems, ensuring functional safety, enabling learning in virtual environments through simulations, and managing varying levels of autonomy.

Recommendations

A comprehensive view reveals important opportunities for research, development, and transfer initiatives to harness the potential of robotics for economic growth and addressing societal challenges. This white paper explores the concept of learning through interaction, considering AI, interaction, simulation and autonomy in robotics in closer relation to one another. This means that, in addition to becoming intelligent systems through AI, robots will also be able to continue learning through interaction. This way, the concept of learning through interaction enables the gradual and partial automation of new domains, as well as the adaptation of robotic systems to new tasks, requirements, and environments. In the future, greater consideration should be given to this aspect when developing strategies and measures, in order to make progress towards interactive and learning robot systems as shown in Figure 1.

Research and development in the field of robotics should therefore promote modularity and synergies across application areas in order to reduce costs and accelerate innovation. Key topics include the integration of AI, hardware, and software, the promotion of interdisciplinary collaboration, and real-time capabilities through approaches such as edge AI. Equally important are safety concepts and ensuring the quality of human feedback within the learning process. Another central focus is the collection and preparation of data to enable deep learning. In addition, the development of variable autonomy and the adaptability of robots should be advanced to ensure broader applicability.

To support the transfer of interactive and learning robotic systems into real-world practice, greater emphasis should be placed on analyzing the economic viability of robotic solutions. This includes examining lifecycle costs and company performance indicators before and after the introduction of robots. Pilot projects involving participatory research that engage relevant stakeholders early in the process, such as businesses, employee representatives, trade unions, technical inspection associations, engineers, scientists, and end users including people in need of care and their families, help build trust in the technology and accelerate market readiness. To test robotic systems under realistic conditions and identify barriers to adoption, real-world laboratories and testing environments should be further expanded.

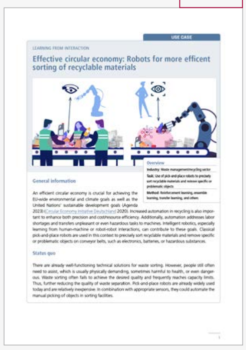
In addition, public discourse on the use of AI in robotic systems should continue in parallel with technological development, with a particular focus on ethical issues regarding autonomy and interaction. Stakeholders from various sectors, including affected individuals such as people in need of care, should collaborate in expert groups or forums to define ethical standards and boundaries for application. In fields such as medicine and caregiving, questions of reimbursement and economic feasibility must also be addressed. Furthermore, standardization bodies should advance clear technical standards for the certification of interactive and continuously learning robotic systems.

Application scenarios for AI

Wearable Robotics: Personalized support and physical rehabilitation

Care-supporting robotics: Individual care and assistance

Sanding, polishing, varnishing: Personal robots for craftspeople



Effective circular economy: Robots for more efficent sorting of recyclable materials

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