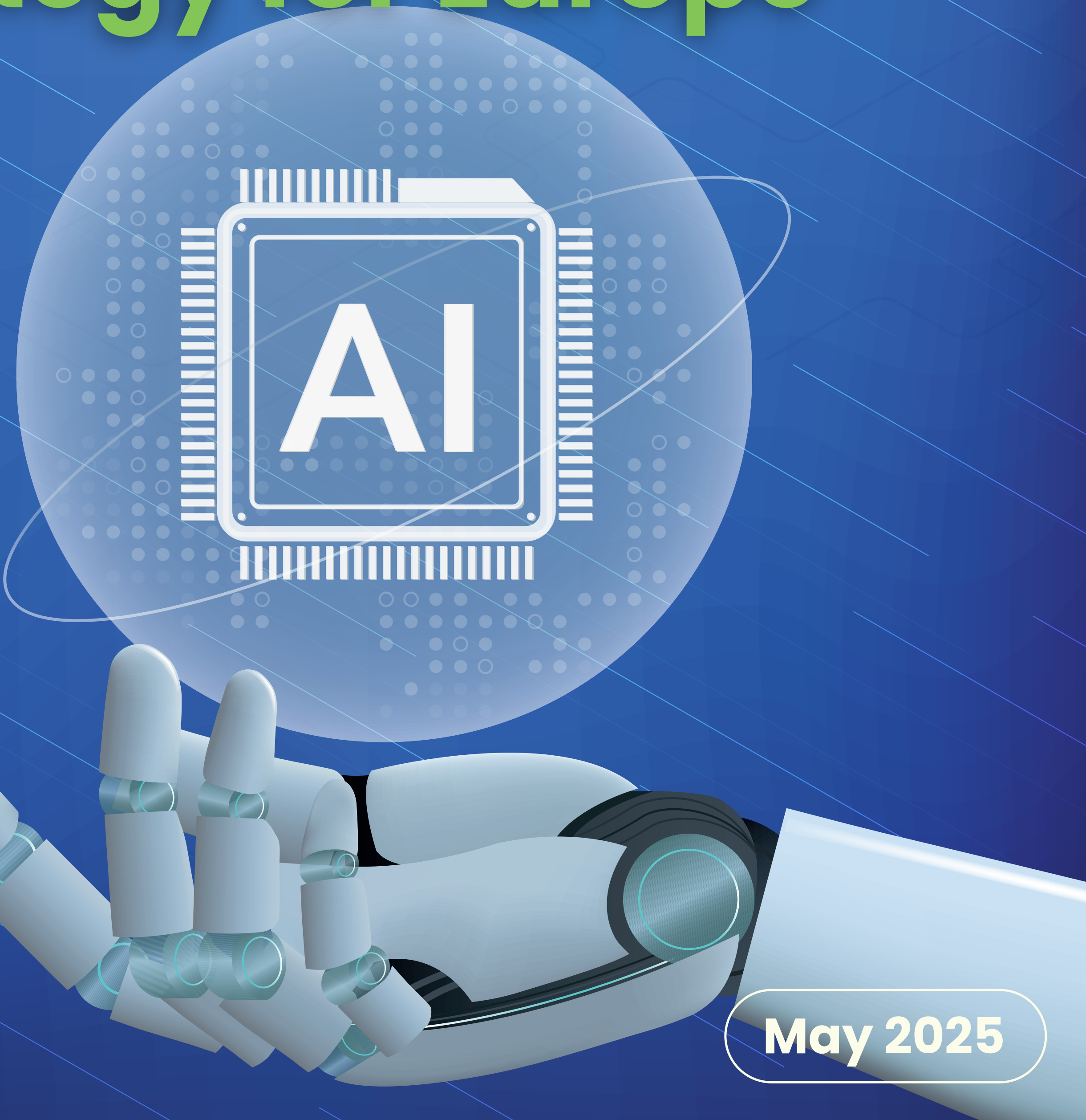
The AI Data Robotics Association

AI-powered robotics
Strategy for Europe



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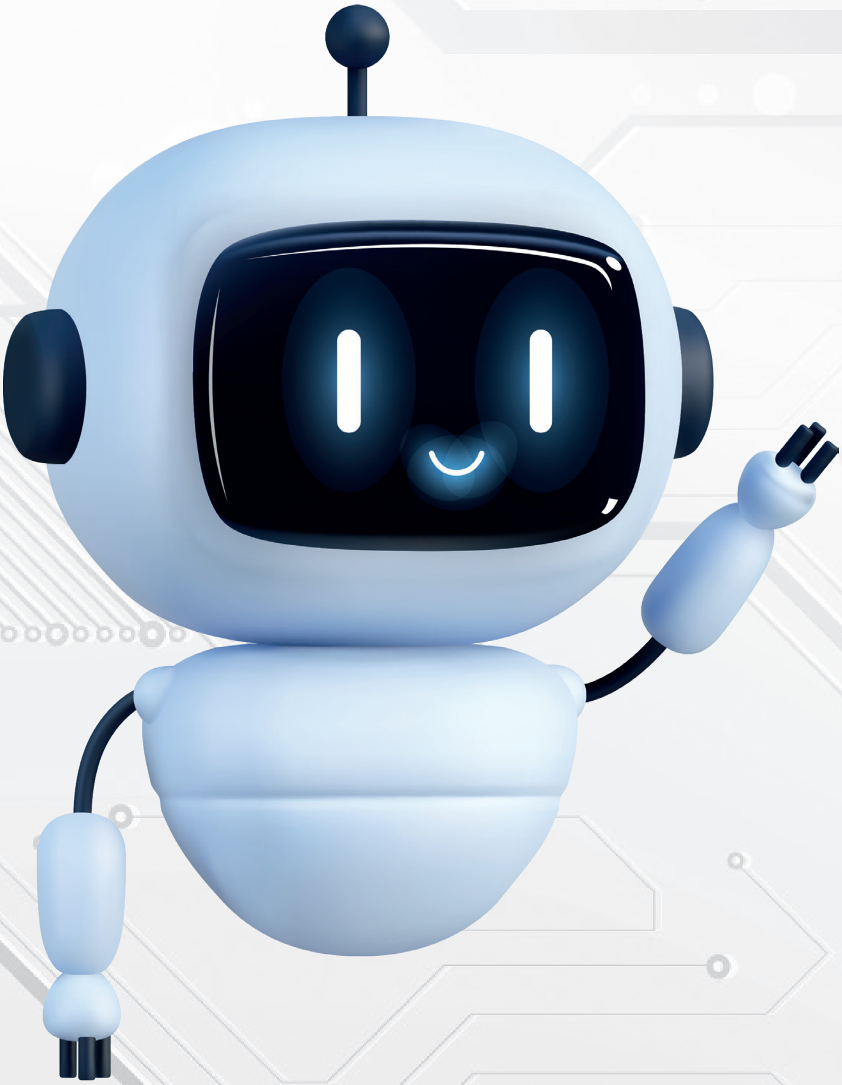

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Pierre-Brice Wieber, INRIA

Philippe Xu, ENSTA

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- Emanuel Sousa, ECG Freek Stulp, DLR
- Iria, Galinanes, CTAG Jon Agirre, TECNALIA Jozef Geurts, INRIA Judith Dijk, TNO Christophe Leroux, CEA
- Morten, Irgens, CLAIRE-AI
- Rodrigo Sedano, ITCL Sabine Demey, IMEC Stavros Ntalampiras, UNIMI Stefan Vanbaelen, IMEC Stefan Leiinen, NLAIC
- Edward Curry, INSIGHT-CENTRE Francesco Ferro, PAL-ROBOTICS Juha Roning, UNIVERSITY OF OULU
- Petri Myllymaki, UNIVERSITY OF HELSINKI Marie Hélène Pautrat, INRIA
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Executive Summary

This document presents a strategy for developing AI-powered robotics in Europe.

It has been just two years since AI changed what we thought possible. The use of data at a massive scale has made it feasible to ask computers for results instead of giving them step-by-step instructions. In just one year, the generative AI breakthrough has extended to robotics, setting off a race that seeks to move away from rigid, pre-programmed machines towards adaptable, autonomous systems capable of interacting with humans in complex, real-world environments.

Europe stands at a critical crossroads in this race. The United States and China have taken an early lead, harnessing unified markets, global digital platforms, and access to real-world data to forge ahead towards general-purpose robotics. China is also leveraging its industrial ecosystem to drive down the cost of new robotics systems. Despite its academic and industrial excellence, Europe is constrained by market fragmentation, regulatory complexity, lower computing power, higher energy prices, reduced access to capital and a fragile robotics industry. It seems impossible for us to compete on these terms.

Nor should we.

The endgame of the race towards general-purpose robotics is not yet within reach. Despite increasingly impressive demonstrations, the road towards reliable, robust AI-powered robotics is still fraught with uncertainty. We do know, however,

- that new AI architectures will be needed to control robotics reliably and safely,
- more data will be needed to develop new multimodal models,
- more computing power will have to be deployed to train them,
- and more energy and material resources will be necessary.

However, in a world of finite resources, exponential paradigms are unsustainable.

Over the next decade, Europe will face increasingly difficult demographic, economic and environmental challenges. Meeting them will require deploying robotics at a wider scale, and the convergence between AI and robotics can facilitate this process. In this effort, our limiting factors can become our strengths. Europe can forge its own way:

- By leveraging our industrial data and our leadership in mechatronics.
- By building up our capacity in edge computing and networked HPC.
- By prioritizing energy-efficient, frugal AI and robotics solutions.
- By deploying hybrid AI-powered trustworthy robotics aligned with European values.

In sum, rather than catching up to a paradigm that might lead to robots that are “good enough” to replace humans in some instances, Europe can and should strive to develop and deploy a paradigm that leverages our unique strengths and targets industrial-grade performance from the outset. The technological and industrial development efforts necessary to achieve this goal will also give European robotics an edge as energy and resource constraints increase globally.

Our vision: a European AI-powered Robotics Revolution

We envision a future for Europe where AI-powered robotics transform our industry, environment and economy. They will harness the power of artificial intelligence and the convergence between software and hardware technologies, but will not sacrifice the safety, security and privacy of European citizens for the sake of speed and scale.

The robotics solutions that will emerge in critical fields such as manufacturing, healthcare, agriculture, infrastructure, construction and maintenance, mobility, security and social robotics, will be multi-purpose and at the service of human activities.

Their underlying components, technologies and solutions will be frugal and sovereign, protecting our strategic independence and allowing us to safeguard European values.

The resulting European AI-powered robotics paradigm will be valuable, safe and robust. A vibrant European robotics ecosystem and its international partners will deploy it worldwide, and it will be key to meeting some of the toughest global challenges in the years to come.

The pillars of the strategy

Despite Europe's strengths in research, technology and industry, we are very far from the objective, and time is of the essence. This vision is not beyond our reach, but enacting it will require relentless action and focus in three areas:

1. Accelerate the capabilities of European AI-powered robotics solutions

- Autonomy and adaptability: develop integrated, co-optimized hardware-software systems for safe, autonomous robots that thrive in unstructured environments.
- Frugality: disrupt energy and power consumption, electronics and computing, sensing, actuators, motors and drives, and material efficiency to enable widespread deployment.
- Safe operation and human-centered interaction: build trustworthy hybrid neurosymbolic AI stacks, human-ready actuation and soft robotics technologies to allow robots to perform in human environments and in complex, high-value applications.

2. Bring AI-powered robotics solutions and components to market more effectively

- Prioritize high-impact applications in each sector, monitoring and adapting as new solutions become feasible.
- Promote connected, shared data and computing infrastructures, in particular sectorial dataspaces and networked HPC.
- Deploy an ambitious challenge-based approach with collaborative competition to fast-track robotics solutions and critical components and ignite new ventures.

3. Build up a robust European robotics ecosystem

- Take urgent action to protect the existing EU robotics industry. Its current fragility makes them vulnerable to foreign dumping and other aggressive measures. Without this critical base, it will not be possible to expand and deploy a sovereign AI-powered robotics ecosystem.
- Scale up and address the gaps in the robotics value chain starting at the OEM level, and extending into robotics components, onboard energy, and electronics.
- Improve capital flows and risk-taking to launch and grow robotics spinoffs and ventures.
- Facilitate compliance with regulations, improving standards and supporting SMEs to reduce certification efforts
- Educate the scientists, engineers and citizens that will build and benefit from AI- powered robotics.

The alternative to the vision proposed is not simply a missed opportunity for increased productivity, but a loss of relevance and economic power that will damage every industry sector and our society. More importantly, we might have to accept a data, AI and robotics paradigm that threatens our sovereignty, our wellbeing and our core values.

In order to avoid such a future and make this vision a reality, we must overcome the problems of fragmentation and speed and concentrate our efforts. Building a European AI-powered robots paradigm will require unprecedented cooperation across European initiatives and member States, but also amongst industry, academia and technology actors.

The following pages give an overview of the different points that we believe are necessary to achieve this vision.

1. Introduction

Europe at a crossroads: the drive towards AI-powered **robotics**

The global drive to develop AI-powered robotics has entered a decisive and transformative era. Less than three years ago, AI redefined what we believed to be possible by leveraging vast amounts of data and transformer architectures. In the last year alone, the generative AI breakthrough has extended its reach to robotics, unleashing the shift from rigid, pre- programmed machines to adaptable, autonomous systems capable of thriving in complex structured and unstructured environments. The race toward general-purpose robotics has begun.

At the heart of this race lie profound challenges that demand advancements in the convergence of AI, robotics hardware, energy efficiency, and computing power. The United States has surged ahead by leveraging its global digital platforms, access to data, capital and computing resources. China has placed an emphasis on developing an industrial value chain that will drive down the cost of physical general purpose robotic platforms, also leveraging its unified market and access to data. Yet Europe finds itself at a critical crossroads. Despite our world-leading academic excellence, engineering capabilities, and trustworthy AI frameworks, Europe faces systemic challenges: market fragmentation, regulatory complexity, technological gaps, and fragile industrial ecosystems. Competing on the same terms as the US and China is neither feasible nor sustainable for Europe... but it does not need to be.

Europe has the opportunity to forge its own way—to leverage its distinctive strengths and build a robotics strategy that prioritizes frugality, sustainability, and trustworthiness, in contrast to the increasingly unsustainable exponential demands of current AI-powered systems. Europe's vision must be bold, pragmatic... and resolutely European: develop robotics that empower industry, protect our independence, and uphold our societal values.

This chapter explores the current state of play and drivers in the global robotics race, while setting the stage for a vision of coordinated European leadership in AI-powered robotics.

Closing the data-AI-hardware **loop**

AI-powered robotics demand the seamless integration and co-optimization of advanced algorithms and cutting-edge hardware—a synergy that we call closing the data-AI-hardware loop. While AI algorithms have achieved groundbreaking capabilities, their full potential cannot be realized without parallel advancements and convergence with robotics for energy-efficient computing, materials innovation, and adaptable hardware technologies. This data- AI-hardware loop is not only limited to the convergence and adaptation of embedded hardware and software (for example, to increase agility, dexterity, and autonomy), but also with regards to the interplay between the robot's software and its physical architecture, actuation and sensors, which will be critical to increase the performance and efficiency of AI- powered robotics overtime.

Europe must seize the opportunity to lead in this integration, designing robots that are not only intelligent but also adaptable, energy-, and capable of operating autonomously in real- world environments.

To achieve this, Europe must prioritize:

- **Autonomy and Adaptability**: Developing integrated hardware-software systems that enable robots to thrive in unstructured, real-world environments while ensuring safe and reliable performance.
- **Frugal and Energy-Efficient Solutions**: Disrupting the status quo in both infrastructure and embedded computing, energy storage, and electronics to create robotics systems that are both scalable and resource-efficient.
- **Trustworthy Hybrid AI**: Advancing hybrid AI stacks and human-centered action systems to ensure that robots are safe, transparent, and aligned with European values.
- **Next-Generation Materials**: Investing in innovative materials, including lightweight composites, soft robotics, and biomimetic technologies, to enhance flexibility, durability, and performance in dynamic applications.
- The emergence and reinforcement of European physical robotics platforms and their supporting value chains and ecosystems

This focus will position Europe at the forefront of sustainable, scalable robotics innovation that meets the economic, environmental, and demographic challenges of the coming decade.

Europe's strengths

Europe possesses the foundational strengths necessary to lead in the AI-powered robotics revolution:

- **World-class research and innovation**: Europe is home to leading research institutions and a highly skilled academic workforce dedicated to robotics, AI, and engineering.
- **Ethical and trustworthy AI**: European leadership in trustworthy AI technologies is key to deploying solutions that embody transparency, fairness, and societal benefit.
- **Industrial and Manufacturing Excellence**: Europe's strong industrial base, particularly in mechatronics, automation, and manufacturing, creates a natural platform for scaling robotic solutions.

These strengths can give Europe a critical competitive edge. However, systemic hurdles—including fragmentation, technological gaps, and regulatory inconsistency—continue to inhibit Europe's ability to transform its potential into leadership.

- **Fragmentation:** Divergent funding mechanisms, industrial priorities, regulatory
- frameworks and market fragmentation limit Europe's capacity to act cohesively.
- **Technological Gaps:** Europe's robotics and AI hardware ecosystem lags behind in key components including sensors, microelectronics, and actuators, limiting scalability.
- **Regulatory Complexity:** Varied national regulations create obstacles for cross-border collaborations and slow innovation. The difficulty of identifying and complying with applicable regulations is a further challenge.

To overcome these challenges, Europe must act with urgency and align policy, research, industry and education to unlock the potential of AI-powered robotics in Europe and scale it up worldwide.

Technological Drivers: Building the Future of Robotics

Europe's strategy must target the technological domains that will drive the future of robotics:

1. **AI and Machine Learning**: Next-generation AI models, including hybrid neuro- symbolic, multimodal, and frugal AI, will enable robots to achieve higher levels of autonomy and decision-making in unstructured environments, while ensuring energy and computational efficiency.
2. **Energy and Computing**: Innovations in energy-efficient edge computing and onboard energy storage, will allow robots to operate autonomously for extended periods and process complex AI tasks in real time, without overwhelming resource demands. Networked high-performance computing (HPC) will enable to train new AI models effectively.

- **Materials Science and Mechatronics**: Advances in biomimetic materials, lightweight composites, and soft robotics will enable frugal, adaptable, and durable robotics that can perform in human environments while supporting resource-conscious design.
- **Connectivity and Edge Technologies**: Integrated communications systems, sector- specific dataspaces, and edge computing infrastructures will facilitate real-time decision-making, foster collaboration between robots, and **integrate robotics seamlessly into larger industrial and societal networks**.

We must accelerate progress in these domains to achieve sustainable, scalable robotics solutions that achieve frugality, trustworthiness, and resource efficiency.

A transformative European robotics ecosystem

The path forward for Europe demands bold action beyond existing research, technology and innovation paradigms. The focus and pace of innovation necessary to achieve and maintain leadership in AI-powered robotics will require specific actions:

1. **Accelerating technology-to-solution pathways**: Implementing challenge-driven approaches that fast-track robotics technologies and solutions into key sectors like manufacturing, healthcare, agriculture, mobility, security and infrastructures, leveraging investment and partnerships driven by European industry end users.
2. **Building Industrial Ecosystems**: Supporting the growth of industrial ecosystems for both robotics solutions and critical components, including embedded electronics,sensors, motors, drives and advanced actuators, and energy systems, but also adapted high-power computing networks and sustainable data spaces and AI solutions.
3. **Strengthening Robotics OEMs**: Scaling up Europe's robotics original equipment manufacturers (OEMs) in traditional sectors like manufacturing and expanding their presence into new strategic fields such as mobility, urban maintenance, security and healthcare.
4. **Aligning Policy and Regulation**: Supporting and facilitating the identification and compliance process for companies, leading to innovation that sill upholds European values of safety, transparency, and accountability.
5. **Fostering Cooperation**: Deepening collaboration among member states, the European Commission, academia, research technology organizations (RTOs), and industry to accelerate innovation and deployment.

6. **Investing in Education and Talent**: Building a skilled workforce capable of driving the next generation of robotics, from fundamental research to applied engineering and system integration.

The aim cannot be merely to build up and maintain the competitiveness of Europe's robotics ecosystem. We must achieve strategic independence, protect our societal values, and address the urgent demographic, environmental, and economic challenges of the decade ahead. Through collective action and relentless focus, Europe can aspire to lead the world in developing and deploying AI-powered robotics that are effective, frugal, and trustworthy.

The following chapters explore Europe's economic, environmental and societal challenges, and its role in the rapidly evolving international landscape, outlining the strategies and technological advances required to secure leadership in the age of AI-powered robotics.

2. Societal challenges and visions for AI-powered robots in Europe

This chapter outlines the societal challenges Europe faces today, and offers a vision for AI-powered robotics as a solution in key sectors, providing insight into their evolution and impact.

Societal Challenges Facing Europe

Europe faces an array of societal challenges that necessitate the deployment of AI-powered robots. These challenges span demographics, economics and the environment. While our academic, industrial, and technological foundations are strong, we must overcome our inherent fragmentation and address barriers like regulatory complexity, high energy costs, and lack of unified market structures to remain competitive.

Demographic Shifts and Labour Shortages

Europe's population is aging rapidly. By 2050, more than a third of the population will be over

60. This demographic shift is exacerbating labor shortages across sectors including manufacturing[1], healthcare, and agriculture. With fewer people available to work, particularly in manual and caregiving sectors, the demand for robotics is escalating. These robots could fill gaps in the workforce by taking over hazardous, repetitive, and physically demanding tasks, or by providing assistance in caregiving roles.

Economic Pressures and Resource Scarcity

Europe's economy is under pressure from resource scarcity, as raw materials critical for AI and robotics development become harder to access. The global supply chain for key elements like rare earth metals, needed for semiconductors and robotics, is strained. Alongside this, the demand for computational power and energy required to support AI models and robotics systems is rising, posing sustainability concerns. Energy-efficient robotics powered by AI, and frugal computing will be essential for tackling these challenges while supporting economic growth. To this end, we must put more emphasis into hardware and software co-optimization. Furthermore, the resulting robotics solutions can prove a game-changer in applications such as automatic disassembly, contributing to the circular economy and mitigating resource scarcity[2].

1 https://www.eurofound.europa.eu/en/publications/2024/company-practices-tackle-labour-shortages

2 "How AI and robots help with e-waste recycling", DLD News, 6 September 2023. https://dldnews.com/how-ai- and-robots-help-with-e-waste-recycling/

Environmental Sustainability

Europe is exposed to the risks of climate change, which threaten our energy and **food security**, our ecosystems, infrastructures, water resources, stability and health[3].

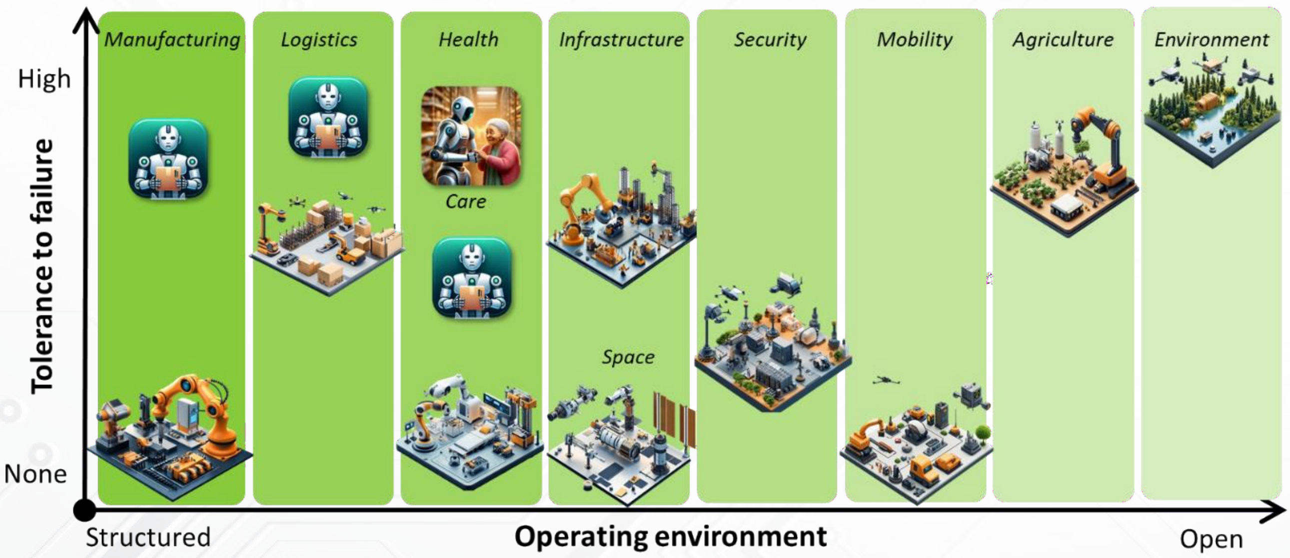
The European Green Deal, aiming for carbon neutrality by 2050, outlines a clear direction for Europe's sustainability goals. However, addressing the climate crisis requires more than just policy reforms. It requires the deployment of advanced technologies that can reduce carbon footprints across industries. AI-powered robots offer an opportunity to make industries more sustainable by optimizing energy use, reducing waste, and enhancing efficiency. Robots equipped with AI can also help monitor and maintain natural ecosystems, track pollution, and improve resource management.

Visions for European AI-powered **robots**

As these challenges mount, Europe must turn them into opportunities. Our vision for AI- powered robotics is one where these systems play an integral role in solving societal problems—transforming industries, improving lives, and driving sustainability.

Transforming Key Sectors with AI-Powered Robots

The full potential of AI-powered robots lies in their ability to adapt, learn, and interact autonomously. These capabilities can transform industries and sectors that are vital for Europe's economy and social wellbeing.



The chart above shows different application areas for AI-powered robotics. The ability of AI-powered systems to operate in open, unstructured environments gives them a distinct advantage in fields such as agriculture, the environment, and mobility. However, as we have mentioned, the current state of the art of the technology is insufficiently robust to allow its full deployment in safety-critical applications, or in applications where repeatability and accuracy are key. For this reason, areas such as mobility have taken a long time to mature. Nevertheless, we can see that in many application domains, there are families of tasks that do not carry stringent safety and

3 European Environment Aaa cy, European Climate Risk Assessment Executive summary, Publications Office of the European Union, 2024, doi:10.2800/204249

performance requirements. This is the case, for example, of intralogistics in a manufacturing environment. "This low-hanging fruit" is often the starting point of the deployment of AI-powered robotics in each sector, with gradual performance improvements leading to wider adoption and greater value creation. However, as we will see at the end of this section, some application domains already present great potential in the short to medium term.00

1. Manufacturing: adapting to new production paradigms

In the manufacturing sector, robots powered by AI will break free from traditional, rigid programming paradigms. Today's industrial robots are limited by their inability to adapt to changing production requirements, and adjusting them to handle new tasks or workflows often requires significant time and the intervention of highly skilled experts. AI-powered robots will be able to reconfigure production lines on the fly, learning from their environment and adjusting processes without requiring human intervention.

In these AI-driven systems, multi-tasking robots will be able to work collaboratively alongside humans[4], boosting production efficiency and enabling a more flexible approach to manufacturing. These robots will have real-time learning capabilities and autonomous decision-making, which will allow them to operate in complex, unstructured environments— adapting to different types of production and rapidly adjusting to changes in demand. This is important for **high-mix, low-volume production** environments where agility is key.

One particular area of manufacturing where AI-powered robotics can have a significant impact is in recycling. The recycling potential of waste from many high-value products and systems, for example electrical and electronic equipment (WEEE) and electric systems (e-motors, power converters and e-batteries) for reuse or recovery of secondary critical raw materials is not being exploited enough. The challenges involved (e.g. dexterity, uncertainty in the condition of components and fasteners) have been too difficult to overcome so far with traditional robotics, and as a result, recycling is generally outsourced to other countries where manual labor is used. To counteract the current shortage of skilled workers and ensure that the processes are economically viable, an increase in the Level of Automation (LoA) of disassembly process is crucial. In this context, advances in cognitive robotic methods and technologies are necessary to help operators to be context-aware and to manage uncertainties and external factor in disassembly. The specific challenges are:

- Development of breakthrough solutions based on mechatronics and sensing for efficient AI-powered manipulation and perception facing the uncertainties in recycling/remanufacturing.
- Development of innovative AI-based methodologies (multimodal AI) to provide reasoning capabilities and product or process information, to help humans to be context-aware and to interact and communicate with them.

4 C. Gkournelos, C. Konstantinou, S. Makris, "An LLM-based approach for enabling seamless Human-Robot collaboration in assembly", CIRP Annals, Volume 73, Issue 1, 2024, Pages 9-12, ISSN 0007-8506, https://doi.org/10.1016/j.cirp.2024.04.002.

2. Logistics: streamlining the supply chain

AI-powered robots will revolutionize logistics by improving the speed, efficiency, and flexibility of supply chains. With AI integrated into logistics systems, robots will autonomously navigate warehouses, delivering materials to workers, organizing inventory, and optimizing transportation routes. These robots will not only carry out repetitive, physically demanding tasks, but also learn to predict and prevent supply chain disruptions, improving overall efficiency.

A critical challenge in logistics today is the lack of autonomy in managing complex, multi- faceted tasks. In the future, AI-powered robots will use real-time data and environmental inputs to predict and optimize logistics flows, thereby enhancing operational efficiency and reducing delays. Whether in warehouse management, last-mile delivery, or transportation logistics, the role of AI-powered robots will be pivotal.

3. Health and care: enhancing care, interaction and precision

Healthcare is one of the most promising sectors for AI- powered robotics, and also one where the need for solutions will become critical in the coming years. The increasing number of citizens with care needs[5], compounded by a staff shortage in the healthcare sector creates a critical need for robotics solutions. Robots can assist with a wide range of tasks, from surgery to rehabilitation, and even elderly care. In surgery, AI-powered robots will provide surgeons with enhanced precision, allowing them to perform minimally invasive procedures with greater accuracy, reducing recovery times, and improving outcomes. For elderly care, robots can provide companionship and assistance with daily activities, alleviating some of the pressure on human caregivers.

In rehabilitation, AI robots will help patients recover from injuries by assisting with physical therapy through personalized routines. With adaptive learning systems, these robots will evolve alongside the patient's progress, offering targeted support and tracking recovery in real time. AI-powered robots will also be essential in providing remote healthcare services in underserved or rural areas, expanding access to medical support and reducing the burden on healthcare systems.

Social robotics will play a transformative role in how humans interact with machines, especially in settings that require empathy, understanding, and emotional intelligence. These robots are designed not just for practical tasks but to enhance human well-being, support companionship, and provide assistance in everyday life.

In elderly care, for example, AI-powered robots will serve as companions for the elderly, offering support and assisting with daily activities such as mobility assistance, medication reminders, and entertainment. These robots can use natural language processing and other sensors to gauge the emotional state of their users and respond in ways that foster a sense of companionship, addressing loneliness and improving quality of life. We should nevertheless note that emotion recognition is a double-edged sword that creates the potential for manipulating human users.

5 European Commission, Green paper on ageing, Publications Office of the European Union, 2022, https://data.europa.eu/doi/10.2775/785789

Further technological progress is indispensable to ensure that safeguards can be put in place against abuse before deploying this technology.

Additionally, in the realm of education, social robots will become invaluable assistants in classrooms and on-the-field lifelong learning, helping to facilitate personalized learning for students, particularly those with special needs. By leveraging AI's ability to adapt and learn from interactions, these robots will tailor their educational approaches to individual students, offering them a more personalized and supportive learning experience.

Social robots will not only assist in homes, schools and workplaces, but also in hospitals, where they can help monitor patient status, provide reminders, and offer companionship, helping to reduce stress and improve patient outcomes.

4. Agriculture and food production: revolutionizing food production practices

AI-powered robots have a massive role to play in transforming agriculture. These robots will be capable of performing tasks such as planting, harvesting, and crop monitoring. By utilizing AI to optimize agricultural processes, robots will significantly increase yields, reduce waste, and ensure sustainability. For example, robots equipped with vision systems and AI algorithms can detect pests or diseases in crops early, reducing the need for harmful pesticides and minimizing environmental impact.

AI robots will also make farming more efficient by automating repetitive tasks and optimizing irrigation, ensuring that resources like water are used more effectively. These systems will be particularly beneficial in precision farming, where robots analyze environmental conditions and soil data to make real-time decisions that increase the efficiency of planting, harvesting, and crop management.

5. Infrastructure maintenance: safeguarding Europe's foundations

The construction and maintenance of critical infrastructure— such as roads, electrical networks, sanitation systems, and other utilities— is a challenge that has only grown as Europe's infrastructure ages. The amount of investment necessary for the development and upkeep should not be understated: the sector has a similar size to manufacturing (in the range of trillions of Euros), with a similar level of direct employment (in the 10s of millions) as the manufacturing sector. The potential for cost reduction through automation is very high: AI-powered robots will become indispensable tools in maintaining and monitoring these networks, ensuring the long-term functionality and safety of essential services.

For road maintenance, robots will be able to autonomously patrol and inspect roadways, identifying cracks, wear, or other hazards before they become significant problems. Equipped with advanced vision and AI analysis, these robots will provide real-time feedback and initiate repairs autonomously, such as filling potholes or cleaning drain systems. This proactive approach will extend the lifespan of infrastructure while minimizing disruption to traffic.

In electricity and sanitation networks, robots will inspect and repair power lines, underground cables, and sewage systems. Drones and autonomous rovers will be able to access difficult or hazardous areas—like remote locations or cramped spaces—where human workers are at risk. By utilizing AI to analyze data from sensors and environmental factors, these robots can predict failures, conduct routine maintenance, and identify leaks or faults in real-time.

This approach will increase the efficiency of infrastructure management, reduce maintenance costs, and enhance safety, particularly in hazardous environments.

Urban areas face significant challenges related to infrastructure, waste management, environmental monitoring, and general city upkeep. AI-powered robots will be central to making cities smarter, more sustainable, and easier to manage, offering innovative solutions that address a range of urban maintenance needs.

Robots will take on a variety of tasks in urban maintenance, from waste collection to street cleaning and public space upkeep. Autonomous robots equipped with AI will navigate city streets, collecting garbage and recyclables, while also using sensors to identify areas in need of cleaning or repairs. These robots will be able to operate during off-peak hours, minimizing disruption and maximizing efficiency.

AI-powered systems will also monitor environmental quality in cities—tracking air and water pollution, temperature, and noise levels—and provide real-time data to city officials for decision-making. This data will help ensure that cities maintain a high standard of living for their inhabitants while also reducing their environmental impact.

In the context of urban planning, AI-powered robots will assist in monitoring the condition of buildings, bridges, and other infrastructure, ensuring that issues are detected early and maintenance is prioritized effectively.

6. Mobility: Revolutionizing Transport and Movement

AI-powered robots will significantly transform the way people and goods move within cities and across regions. In the mobility sector, autonomous vehicles, drones, and robotic transport systems will work together to create seamless, efficient, and sustainable transport networks.

Autonomous delivery robots will transform the logistics and courier industry, enabling last-mile delivery with no human intervention. These robots will navigate urban environments, avoiding obstacles, and utilizing AI to optimize delivery routes. Drones will take on the task of transporting goods over longer distances, reducing congestion and enabling faster, more efficient delivery.

In public transportation, AI-powered vehicles—ranging from buses to trams and even flying taxis—will become commonplace, allowing for more flexible, on-demand services. By using AI to optimize routes, adjust to traffic conditions, and improve fuel efficiency, these systems will reduce environmental impact while enhancing mobility.

In personal transport, autonomous vehicles will offer enhanced safety, adaptability, and convenience. They will not only drive on highways but also operate in complex urban environments, such as busy streets or crowded parking lots, with advanced sensors and AI that ensure safe, efficient, and comfortable travel for users.

7. Security: Strengthening Safety with AI-Powered Surveillance and Response

Security is a critical concern for both individuals and society. AI-powered robots will play an increasing role in ensuring public safety through surveillance, monitoring, and response capabilities. These robots will be integrated into urban and rural environments, working alongside law enforcement to detect threats and provide real-time responses.

Autonomous drones will be deployed for surveillance, providing live feeds to security centers to monitor large crowds at events or patrol borders, airports, and other sensitive areas. AI-powered robots will use image recognition and behavioral analysis to detect suspicious activity, track movements, and alert authorities to potential threats. The deployment of AI-powered solutions that respect privacy and human rights is critical.

In disaster response scenarios, AI robots will be able to assess the damage and assist with rescue operations in areas that are unsafe for humans to enter. Equipped with sensors and communication devices, they will be able to locate survivors, deliver supplies, and assist emergency responders in real time.

8. Environmental services

Caring for the environment requires an understanding of the situation on the ground and the ability to act. AI already holds immense potential as a tool to assist humans in developing and designing approaches to reduce energy costs, enhance overall energy utilization efficiency, and lower carbon emissions.

Using AI, robots can learn from multimodal data, generate diverse and creative behaviors, and adapt to changing

situations, thus enabling scaling up existing climate and environmental services solutions and offering novel solutions to mitigate and adapt to climate risk. AI-powered robots can therefore serve as a multiplier by allowing the rapid deployment of climate solutions at scale, thereby accelerating the pace and impact of climate action.[6] Up to now, existing AI systems include tools already helping to tackle climate change by e.g. mapping deforestation, monitoring of icebergs melting, predicting weather patterns and climate disasters, making waste management more efficient, reducing plastic pollution in oceans, or decarbonizing industry operations by tracking their emissions.[7] Despite the great potential of using robotics to accelerate the deployment of climate solutions, the field does not have the same level of attention as the application of AI for climate actions.[8] Support for climate robotics, a new and rapidly growing field that uses AI-powered robotics to scale climate action, can serve Europe's commitment to tackling environmental challenges.

6 Climate Robotics Network, White Paper Series, Why climate robotics?, 2024, https://climaterobotics.network/research

7 World Economic Forum, 9 ways AI is helping tackle climate change, 2024, https://www.weforum.org/stories/2024/02/ai-combat-climate-change/

8 (2024). Will generative AI transform robotics? Nature Machine Intelligence, 6(6), 579. https://doi.org/10.1038/s42256-024-00862-2

9. Space: Advancing Humanity's Reach Beyond Earth

In the near term, AI-powered robotics will be crucial for improving the efficiency and sustainability of operations in Earth's orbit. These robots will enable autonomous tasks that are currently challenging, such as maintaining satellites, assembling space structures, and servicing space stations. By using AI for real-time problem- solving, robots will be able to perform precise repairs, upgrades, and diagnostics on satellites in orbit, reducing the need for costly human missions and minimizing the risks associated with spacewalks.

One of the key objectives for space robotics in the short term will be the development of autonomous spacecraft that can carry out maintenance on space infrastructure, such as cleaning space debris, refueling satellites, or carrying out technical repairs. These robots will use AI to navigate and analyze space environments, performing tasks like capturing malfunctioning satellites or conducting routine inspections without human intervention.

Furthermore, AI-powered robots will assist in the assembly of large structures in orbit, such as solar arrays or space habitats. These robots will autonomously handle complex assembly tasks, relying on their AI to ensure the structural integrity and safety of the installations, reducing the cost and risk of human involvement.

Europe cannot afford to disregard any of the sectors above. They are all critical to our collective welfare and competitiveness, and all show disruption potential from the introduction of AI-powered robotics. However, the highest priority should be given to the following sectors:

1. Manufacturing: the sector is critical for employment and value creation. Europe possesses a large manufacturing industry that weighs heavy in our trade balance, and the large number of SMEs in European manufacturing value chains will benefit most from flexible, no-code manufacturing robotics. Furthermore, AI-powered robotics also show significant potential for improving circularity in European value chains, lowering the cost of disassembly, sorting and other key recycling processes.
2. Infrastructure construction and maintenance: This sector shows high potential for disruption from AI-powered robotics solutions. The existence of large industry actors and institutional end customers, as well as its economic impact, all call for particularemphasis. The potential of robotics as a vector for 3D printing also presents a key opportunity.
3. Agriculture: The agricultural sector's relatively unstructured environment also stands to benefit from the flexibility of AI in the short term. This sector has a major impact on food security and climate resilience, but needs a considerable amount of support to adopt new technologies.

General characteristics of AI-powered robotics solutions

The different application areas highlighted above share a number of characteristics where step changes in technology are necessary:

- **Higher autonomy and longer-term planning**: In order to reach higher levels of autonomy, robots need to have a detailed understanding of their environment. Constructing these models requires fusing sensor data with different modalities in real time and combining it with task specific domain knowledge. Based on evolving world models, robots can plan the next steps needed to complete a specific task. Planning is particularly challenging in environments where events that were not expected when designing the robot can occur (open world, unstructured environments). For applications in human populated areas, this is inevitable, which is why it is important to ensure planning algorithms can be updated by users, e.g., via human robot interaction. Planning algorithms be explainable, such that robots behave in predictable manners and safety can be guaranteed. This requires robots to be aware of their limitations. Autonomy is not exclusively a software problem. It will require, for example, further efforts in sensing technologies.
- **More dexterity**: Many tasks easily performed by people on a daily basis are still cumbersome or even unfeasible for robots. In order to acquire dexterous behaviors when manipulating physical objects, advanced robotics solutions are required. The main challenges are:
  - The design of dexterous, flexible and agile robotics hands and end effectors, including real-time feedback of the dynamic behavior of the manipulated objects (multimodal data fusion, self-reconfiguring modular design, soft robotics, soft and smart materials).
  - The control and learning strategies, which may benefit from AI-powered solutions, in particular the development of reinforcement learning methodologies bridging the simulation-to-real gap and making use of specific multimodal foundation models that include advanced proprioception (e.g. force-feedback, robotic skin).
- **More embedded computing capacity and fleet level learning**: in order to handle increasingly complex tasks in real-time, including multimodal perception, decision making and interaction with humans or unstructured environments, the embedded computing capacity of each robot must increase. This is particularly true for applications where long-term deployments are expected, and especially where constant connectivity to the cloud cannot be ensured (e.g., infrastructure maintenance, agriculture, environmental services). As robots are deployed in larger numbers, federated and distributed learning mechanisms will become essential to leverage the scale effect of the data and problems encountered, increasing performance and safety through fleet-wide anti-fragile mechanisms. Achieving this vision will require overcoming significant challenges, including energy consumption and thermal constraints, secure data sharing and robust communication protocols, and robust mechanisms to ensure the trustworthiness of fleet learning for robotics systems-of-systems. Additionally, it is crucial that the data capitalization takes place in a manner that respects privacy, as the robots will be in contact with humans in most situations. Advances in techniques such as homomorphic encryption and data anonymization will also need to be implemented in future AI-powered robotics fleets to underpin their learning processes.
- **Higher efficiency and lower consumption**: Further advancements in robotics require that large amounts of data can be processed in real-time and that structures can be found in this data to

ensure that solid decisions can be taken - in both elements AI will be supportive and required. Thus, there is an increasing explosion of the computational complexity to both train and inference AI models that are required from a robotics perspective. Thus, current foundation models can only be built and maintained with very high investments in computational infrastructure. In light of the above-described challenges and this context, it will thus be required to work towards robotics, integrating AI, with a higher energy efficiency and a lower consumption of resources. Achieving this objective will require a co-optimization of the software and the hardware required for both robotics and AI, leading to e.g. specific AI accelerators, optimized algorithms, edge AI elements etc. Overall, it could be summarized as activities on the following topics:

- Design of novel chip technology (transistors, memory concepts).
- Improvements in the domain of new system architectures.
- Improvements on the algorithms, making them more hardware specific.
- Improvements in the hardware and software leading to more trustworthiness and resource-efficiency (energy-efficiency, data- efficiency).

- **Better social adaptation and interaction with humans**: Over the last decades, significant progress has been made in various areas of artificial intelligence, robotic research and human-robot interaction (HRI) and demonstrated in specific, pre- defined settings and scenarios but with very limited ability to systematically orchestrate and adapt these robotic functionalities across different settings, domains, and user profiles. Such predefined scenario-based approaches often hinder a natural, smooth, and safe HRI since the robots lack situational and contextual awareness of the environment and user needs. This is a severe limitation, particularly in situations that require very close assistance with continuous physical interaction.

  To advance toward physically safe and socially acceptable robots that interact robustly with humans, we will need to balance technological advances with ethical safeguards. If robots that mimic human actions are desirable for a more fluid interaction (demonstrating qualities such as anticipation, adaptability and sensitivity, key elements in building trust), respecting privacy and avoiding manipulation are crucial points. The necessary developments include:

  - Development of explainable behaviors of AI-powered robotic skills learned from human-in-loop demonstrations using diverse learning methods for context-aware physical human-robot interaction.
  - Development of user-adaptive control methods for safe and natural physical interaction with human and shared-control autonomy as well as transparent and intuitive communication mechanisms
  - Development of human-oriented hybrid multimodal AI, incorporating foundational models for collaborative AI powered robots.

- **New materials and soft architectures / actuation:** Soft robotics have been explored for many years to improve the safety of robotics, but also to overcome the limitations of rigid robotics systems for many applications (grasping objects, negotiating obstacles, etc.). Although they are a very promising field, they present significant challenges for design and control. The use of artificial intelligence techniques in the design, simulation and control of soft robotics systems (soft materials, structures and actuators) represents a significant area of opportunity that fits perfectly within the AI-powered robots vision that we present, allowing greater autonomy and safety, as well as improving human-robot interaction.

Sustainability and trustworthiness: the European approach

The vision for AI-powered robotics in Europe can in no way be limited to technological aspects. It must encompass developing environmentally, economically and societally sustainable robotics solutions that ensure responsible resource usage and minimize environmental impact. The environmental impact of developing and deploying AI-powered robotics at scale cannot be neglected: the high energy consumption of generative AI poses a serious challenge to the European ecosystem - both from an energy production point of view and from a global warming point of view. For example, the use of large language models (LLMs) in robotics shows a promising jump in capabilities and robustness in scene understanding, human-robot interaction, and action planning[9]. Unfortunately, the currently most widely used Gen AI solutions rely on extensive computing power (hardware, servers, supercomputers, and networking equipment) which means high costs and high energy consumption[10]. Rather than relying on frontier AI models requiring enormous HPCs, Europe should find alternative solutions. Safe and low-carbon Edge AI, enabling running models on local devices with edge computing capacity, as well as the development of Small Language Models, requiring less data and less computing power than LLMs[11] represent different approaches that cannot be developed in isolation, but as part of an edge-to-cloud continuum. This direction serves better Europe´s principles, such as privacy, trustworthiness, and reduced carbon footprint.

By focusing on energy-efficient, low-carbon robotics, Europe can lead the world in creating robots that are not only powerful but also sustainable. AI systems will be optimized for edge computing, reducing the reliance on large data centers and decreasing energy consumption.

A key priority will be to develop AI models and robotics solutions that can operate efficiently on less energy, harnessing the power of locally sourced data and avoiding over-reliance on centralized cloud infrastructures. These efforts will align with Europe's commitment to achieving carbon neutrality by 2050.

Another challenge to be taken into account is the scarcity of natural resources in Europe, which can strongly impact AI-powered Robotics, in particular in the current geopolitical context. When it comes to AI, and not only GenAI, the high computing power needs will require both an intense usage of water and energy, whereby the energy is in certain cases still being produced on the basis of fossil natural resources (e.g. coal). Given the strongly expected increase in AI usage, and thus compute power, both the usage of water and energy is expected to further rise to uphold compute power capacity. As indicated above, approach might therefore need to be found to tackle those resource questions related to water and energy for the particular case of AI compute power.

Furthermore, as indicated in the 2020 European Commission Report on Critical Raw Materials for Strategic Technologies and Sectors in the EU, "the risk to the supply of raw materials and components is potentially high"[12]. While policy actions have been undertaken in the last few years,

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10 EIT Digital, Generative AI, Europe´s quest for regulation and industry leadership, 2024 ISBN 978-91-87253-71-3

11 Schick, T. and H. Schütze,(2021). 'It's Not Just Size That Matters: Small Language Models Are Also Few- Shot Learners', Proceedings of the 2021 Conference of the North American Chapter of the Association for Computational Linguistics: Human Language Technologies (https://doi.org/10.18653/v1/2021.naacl-main.185).

12 https://rmis.jrc.ec.europa.eu/uploads/CRMs_for_Strategic_Technologies_and_Sectors_in_the_EU_2020.pdf

both in terms of natural resource rethinking & recycling, the challenge remains. Furthermore, this is not only a challenge for Robotics, but also for the AI supply chain, whereby one might think of minerals required for semiconductor technology developments and production. A further increase of Europe's global independence in relation to other global regions is therefore to be continued. This can entail several approaches, ranging from replacing scarce resources by other more commonly available resources, a further recycling of natural resources up to achieving independence through mining.

In addition, all the key application sectors that we have presented require a high level of trustworthiness. The low margin of error means that the limitations exhibited by generative AI today would render the deployment of AI-powered robots unreliable and dangerous. The best path forward in this respect is the hybridization of generative artificial intelligence modules and other AI techniques with symbolic AI and deterministic planning and control techniques, as well as the development of supervision technologies and better world models.

We will need to deploy significant efforts in the development of trustworthy AI pipelines from the data collection phase to the supervision and monitoring of the operational domain during robot operation. Europe's leadership in trustworthy AI research is a unique asset that must be consolidated, matured and leveraged in our path towards AI-powered robots.

Conclusion

Europe must embrace its strengths in AI, robotics, and sustainability to build a robust, resilient ecosystem that serves both economic growth and social well-being. By focusing on safe, frugal, and ethically aligned robotic solutions, Europe can lead the world in creating a future where AI-powered robots not only enhance industries but also improve lives, ensuring that European values such as privacy, security, and sustainability remain at the heart of technological advancement. Realizing this vision will require overcoming key challenges in technology development, deployment and scale-up, regulation and education. They will be covered in the following chapters.

3. International State of the Art and EU Strengths

The global robotics landscape is evolving rapidly, fueled by the convergence of Artificial Intelligence (AI), data and robotics (including cutting-edge hardware and advanced software systems). In regions such as the United States and China, massive investments and the exploitation of unified markets have accelerated the development of general-purpose robotics, aimed at transforming industries across the board.

However, Europe, while not yet in a race to match the scale of these players, possesses distinct advantages that set it apart in the global robotics ecosystem. Europe's unique strengths in multidisciplinary research, industrial robotics, and emerging technologies such as 6G, alternative telecommunications technologies, and next-gen battery systems position it for a future where AI-powered robotics can be a driving force in the economy.

State-of-the-art by sector

a. Manufacturing

The manufacturing sector has experienced significant innovation, particularly with the rise of collaborative robots (Cobots) and Digital Twins, which have transformed how production lines operate. In response to the challenges of increasingly dynamic and complex industrial environments, Europe has the opportunity to leverage its strength in mechatronics and industrial robotics to develop adaptable, safe, and efficient AI-powered robotics systems that combine flexibility and productivity.

As manufacturing sectors move toward Industry 5.0, the integration of collaborative robotics will enable closer interaction between humans and machines. With Europe's academic and industrial foundations, it can forge ahead in creating sustainable and frugal solutions that prioritize energy efficiency while advancing automation and production capabilities.

b. Transport & Logistics

The transportation and logistics sector is another critical area for AI-powered robotics. While North America and China lead in scaling up logistics robotics, Europe has a distinct advantage in its capacity to integrate robotics into existing, often complex infrastructure systems.

Through public-private partnerships, Europe can accelerate the deployment of autonomous systems, focusing on hybrid AI solutions that balance efficiency with safety.

c. Healthcare

The healthcare sector stands to benefit from Europe's robust research capabilities, particularly in the integration of robotics in surgery, rehabilitation, and elder care. By focusing on safe human-robot interactions and developing trustworthy AI systems that prioritize privacy and safety, Europe can lead in creating robots that enhance quality of life and contribute to solving the demographic challenges facing the continent.

d. Agriculture

Agriculture, a vital sector for Europe, will see transformative shifts through AI-powered robotics, particularly in precision farming. The European Commission's strong focus on developing sector-specific data spaces can be harnessed to drive AI adoption in agriculture, using data-driven models to enhance productivity while addressing sustainability challenges.

e. Infrastructure maintenance

While significant strides have been made in the development of infrastructure for AI-powered robots, the European approach must emphasize the role of sustainability and adaptability in building robust, interconnected systems. Europe's fragmented market and regulatory landscape present challenges, but they also offer an opportunity for Europe to lead in the development of decentralized systems that foster innovation without compromising the core values of trust and safety.

f. Mobility

Mobility has represented one of the main areas for the application of AI-powered robotics technologies in the last decade. High-potential applications are not limited to autonomous personal vehicles, however: they range from autonomous public transport to personal mobility aids. Europe's leadership in clean technologies and urban planning is particularly useful for these applications. Furthermore, the AI stacks and sensors used in these systems are often common to other robotics application areas, and this domain should continue to receive attention at European level, but the synergies with other robotics areas should be reinforced.

g. Security

In the field of security, AI-powered robots can transform everything from surveillance to disaster response. While nations like the US and China have advanced rapidly in deploying autonomous security systems, Europe's unique strengths in defense robotics and cybersecurity offer a strong foundation for developing trustworthy, ethical robotic systems that respect European values of privacy and individual freedoms.

h. Environmental services

Environmental robotics present a particular area of opportunity where Europe can lead the world, leveraging our leadership in clean technologies to protect natural ecosystems by performing tasks such as automated waste management, deploying solutions to reduce pollution or control pests, or the monitoring of wildlife and natural ecosystems. The demand for such solutions worldwide will increase in the coming years, making AI-powered robotics a candidate technology to achieve sustainable development goals.

g. Space

Europe's leadership in space robotics, particularly through ESA and Horizon Europe, provides a competitive edge in this domain. Space missions, particularly those focused on exploration and sustainability, will increasingly rely on AI-powered robots. Europe's strengths in this area, when coupled with its interdisciplinary research capabilities, could position it as a leader in space robotics innovation.

Technological state-of-art and barriers to the deployment of AI-powered robotics visions

Despite impressive advancements, several barriers remain to the widespread deployment of AI-powered robotics. Key challenges include improving the autonomy and adaptability of robots, ensuring safe operation, and addressing the substantial computational and material demands of cutting-edge AI systems.

a. AI Capabilities

AI has been the cornerstone of recent developments in robotics. From deep learning to generative AI, European researchers are at the forefront of developing AI systems that enhance robotic perception, decision-making, and action. However, challenges such as the need for vast amounts of data, increased computational power, and energy consumption must be addressed to scale these systems effectively. Europe's commitment to energy- efficient AI solutions will be key to its success in competing globally, in particular as players like NVIDIA are opening the way to the generation of synthetic data by means of generative

AI models, in cases where insufficient real-world data is available. Such approaches are particularly (but not exclusively) important for reinforcement learning, which is widely deployed on humanoid robotic platforms. Imitation learning with humans-in-the-loop is also making big strides, and provides an avenue for accelerating the development of new skills and model capabilities.

b. Robotics platforms

The past year has been marked by the resurgence of humanoid robot platforms in the United States, but more particularly in China. Both countries are moving rapidly to create a general-purpose robotics industry. China is emerging as the clear leader, with control of 63% of the global supply chain for humanoid robotics[13], in particular for hardware components, and the number of companies focusing specifically on humanoid robots could be as high as 200. The strategy is driven by the Chinese government, who has allocated over $20bnUSD to support its program. In the United States, the humanoid sector is centered around private enterprises and venture capital, with several billion USD raised by companies like Figure AI, Agility Robotics, and 1X. Their efforts are also backed by tech giants, and as a consequence, US companies are still thought to be leading in AI capabilities and software development. It is important to note that in both instances, the current market for humanoid solutions is very small, hindered by the insufficient performance of current systems. In both cases, the drive for humanoid robots represents a long-term investment.

c. Trustworthiness

As robots begin to operate alongside humans in more complex and dynamic environments, safety is paramount. Europe's emphasis on developing hybrid AI systems that balance autonomy with predictability will be essential to fostering trust in AI-powered robots. The deployment of soft robotics and trustworthy AI frameworks will be critical in ensuring that robots operate safely and transparently, respecting European ethical standards and privacy concerns.

d. Security and Cybersecurity

Robotic systems must be designed with cybersecurity in mind, particularly as they become more

13 https://www.ciw.news/p/humanoid-robots-100?

interconnected in networked environments. Europe's approach to privacy and data protection offers a unique opportunity to develop secure and trustworthy robots that can operate in sensitive environments without compromising personal data or safety.

e. Embedded Computing & Hardware Requirements

The hardware required to support AI-powered robots is advancing rapidly, with edge computing and networked high-performance computing (HPC) becoming central to the development of real-time, autonomous systems. Europe's commitment to developing these technologies will help address the scalability and reliability issues faced by AI-powered robotics. The ability to run complex hybrid AI stacks without the need for a connection to the cloud will be critical in many application areas, and new hardware architectures and players must emerge. Finally, hardware platforms will also play a part in enabling the safety and security features necessary to deploy AI-powered robotics more widely. The capability to simulate potential outcomes for decision making at sufficient speed will be critical in many applications.

European Strengths and Challenges

Europe's ability to capitalize on its strengths in robotics lies in its approach to collaboration, innovation, and sustainability. However, several challenges need to be addressed to ensure that the region remains competitive on the global stage.

a. Fragmentation

The fragmented European market poses a significant challenge to scaling robotics. To overcome this, Europe must focus on promoting shared data and computing infrastructures, particularly through sectorial data spaces, to drive innovation. Coordinating regulatory approaches across European member states will be critical in fostering a more unified robotics ecosystem.

b. Ethics, Data Privacy, and Individual Freedoms

Europe's commitment to upholding ethical standards and protecting data privacy offers a unique opportunity to lead in the development of trustworthy AI-powered robots. By aligning robotics with European values, such as the protection of individual freedoms and privacy, Europe can set the global standard for safe and ethical robot deployment.

c. Strengths in Hardware, Machinery, and Industrial Sectors

Europe's industrial foundation is built on deep expertise in hardware and machinery, and it remains a leader in several sectors, such as automotive, aerospace, and space. By leveraging these strengths, Europe can accelerate the deployment of AI-powered robots across various industries, from manufacturing to healthcare.

In this landscape, the United States, China, and Europe are at different stages of development and face unique challenges. While both the US and China have accelerated their AI-powered robotics capabilities by building unified markets and leveraging expansive access to real-time data, Europe is contending with a fragmented landscape that requires innovation in its regulatory, infrastructural, and cultural approach to data utilization.

Global state-of-play

a. The United States

The US has emerged as a global leader in AI and robotics, driven by its expansive data infrastructures and relatively flexible regulatory environment. The country's ability to quickly mobilize vast datasets, combined with its strengths in cloud computing, edge computing, and high-performance computing (HPC), provides a competitive advantage in developing scalable robotics solutions.

Moreover, the US market benefits from its dominance in digital platforms, which capture and aggregate massive amounts of user and operational data. This data-driven model allows for rapid iteration of AI algorithms and, by extension, the development of more capable and adaptable robots. The availability of large-scale, unregulated data sources—coupled with private sector collaboration—has positioned the US at the forefront of robotics, particularly in areas like autonomous vehicles, smart manufacturing, and healthcare robotics.

However, while the US enjoys substantial access to data, this comes with growing concerns regarding data privacy and ethical implications, particularly as AI systems become more pervasive. The absence of comprehensive, unified regulations poses risks for ensuring the safety, security, and privacy of data and user interactions, which Europe is striving to address through its more structured regulatory environment.

b. China

China is a strong player in the robotics field, propelled by its massive government investment in AI and infrastructure development. The Chinese government's top-down approach to industrial policy, coupled with an ability to amass vast data from a centrally controlled, large- scale population, has positioned China as a leader in both data collection and robotics innovation. The extensive use of facial recognition, surveillance, and e-commerce platforms provides China with unparalleled access to consumer and industrial data, facilitating rapid AI model training and robotics development.

However, China's centralized approach to data governance comes with its own set of challenges. While access to data is abundant, there is little room for individual privacy rights, and data usage is subject to government control, raising concerns about transparency, fairness, and the use of AI in surveillance technologies. As a result, China's model for AI- powered robotics development is not aligned with European values of personal privacy, safety, and data sovereignty. The drive described earlier towards humanoid robotics has allowed China to create an industrial ecosystem that results in physical platform costs up to two thirds less than their American or European counterparts. Given the importance of AI- hardware convergence, it is unlikely that these platforms will become a commodity in the near future.

c. Europe

Europe, despite its academic excellence and industrial know-how, faces several challenges in the race for AI-powered robotics leadership, primarily due to market fragmentation, regulatory complexity, and lower access to real-time data compared to the US and China. The European Union's focus on privacy and data protection, exemplified by the General Data Protection

Regulation (GDPR), places restrictions on how data can be collected and used, which contrasts with the data-driven models in both the US and China.

While these regulations are essential for safeguarding citizens' privacy and upholding European values, they can also limit the availability of data for training AI systems. In Europe, data sharing is often fragmented across sectors, and there is a lack of coordinated, cross- border data infrastructures that could enhance AI and robotics development. This fragmentation, both in terms of data availability and regulatory frameworks, presents a significant hurdle for achieving the scale necessary to compete with the large, unified data ecosystems of the US and China.

The Challenge of Data Access and Regulation: US, China, and Europe

Access to data is a critical determinant of the success of AI-powered robotics, and this is where Europe faces its most significant challenge in the international context. We will now explore how the different regions approach this issue:

a. Data Infrastructures: Availability and Access

In the US, the centralized nature of its tech industry means that data aggregation often happens at the scale of multinational corporations, which can leverage vast quantities of data across their platforms. This allows for the rapid development and deployment of AI-powered robotics. Large players like Google, Amazon, and Microsoft can access and analyze diverse datasets across industries, facilitating the creation of adaptable and autonomous robotic systems.

In contrast, China benefits from government-driven initiatives that encourage large-scale data collection in various sectors. The country has developed smart city initiatives, IoT infrastructure, and facial recognition systems, all of which provide valuable data for AI and robotics development. These systems, although efficient, may not align with international standards of data privacy or ethical considerations, limiting their global acceptance.

Europe, however, struggles with the fragmentation of its data landscape. The EU has made strides with initiatives such as the European Data Strategy, which aims to create a single digital market and promote data sharing across sectors. However, it still lacks unified infrastructures for large-scale, real-time data access, making it difficult to harness the full potential of AI- powered robotics. The European Commission's vision for sector-specific data spaces is a step in the right direction, but it will require coordinated efforts to overcome the regulatory, technical, and cultural challenges associated with data sharing.

b. Regulation and Data Privacy

Regulatory frameworks are perhaps the most significant differentiator between the regions. The US regulatory environment is relatively permissive, especially regarding data collection, which facilitates the rapid growth of AI-powered technologies. However, this approach raises concerns about privacy, bias, and the misuse of personal data, particularly as AI systems become more embedded in everyday life.

China's centralized control over data flows allows the government to dictate how data is used, often prioritizing national security and surveillance. While this gives China a clear edge in terms of data access, it raises questions about the ethical implications of such control, especially when it comes to personal freedoms and individual rights.

Europe, by contrast, places a strong emphasis on protecting data privacy and individual rights, with the GDPR setting the global standard for data protection. However, this regulatory framework can limit the ability of AI developers to access and utilize data at scale. While the EU's commitment to privacy and security is an advantage from an ethical standpoint, it can create challenges for industries looking to rapidly deploy AI-powered robotics solutions, particularly when compared to the more lenient regulatory environments of the US and China.

c. Cultural Differences and Public Trust

One of the more subtle but important factors in data access is the cultural context surrounding data usage. In the US, there is a certain level of trust in private companies to use data responsibly, driven by market-driven incentives. While there are growing concerns about privacy, the general public is more willing to accept sharing if it leads to technological benefits.

In China, the government's control over data is largely accepted due to a more collectivist societal view, where individual privacy may be seen as secondary to national interests. This allows for a more seamless, albeit controversial, integration of data into AI-powered robotics.

In Europe, cultural concerns about privacy, individual freedoms, and data sovereignty are paramount. Europeans tend to be more cautious about how their personal data is used, especially by corporations and governments. This skepticism toward large-scale data usage presents both a challenge and an opportunity for Europe. On one hand, it complicates the development of AI-powered robotics at scale, but on the other, it provides a framework for developing systems that prioritize trust and accountability, which can be a key differentiator.

Europe's Path Forward

Despite the challenges of data fragmentation and regulatory complexity, Europe has an opportunity to carve out a distinct niche in the AI-powered robotics race. By focusing first on meeting industry performance levels, achieving data sovereignty, promoting frugal AI solutions, and prioritizing energy efficiency, Europe can leverage its cultural and regulatory strengths to create a unique value proposition for robotics solutions that align with European values.

To succeed, Europe must continue to invest in shared data infrastructures, such as sector- specific data spaces, and foster cooperation between industry, academia, and government. In parallel, Europe must develop hybrid AI systems that balance the need for data with ethical considerations, ensuring that AI-powered robots respect privacy and operate safely in diverse environments.

Because of the inevitable convergence between data, AI and hardware, and the current maturity level of AI-powered robotics, a two-tiered strategy that pushes for adoption of foreign robotics solutions while developing sovereign solutions is not an adequate path. We therefore propose to focus investment and efforts on the development of a sovereign European technology base and ecosystem for AI-powered robotics that targets our industrial and societal needs, and respects our core values.

4. Challenges and Technology Needs

In the current chapter, we will transition from the challenges outlined for AI-powered robots into the specific technology development needs required to address these challenges. We will explore the core technological priorities that are essential for the successful implementation of AI-powered robots across multiple industries, detailing the infrastructure, research, and innovations needed to propel Europe forward in the global robotics landscape.

The development of AI-powered robots capable of addressing real-world challenges requires addressing several technology gaps. These gaps span across energy, software-hardware optimization, computing capacity and optimized infrastructures, intelligence, safety, and social adaptation, among others. The following sections identify the key technological needs for each of these areas.

Energy and Computing Infrastructure for Fleets

Key challenge: AI-powered robots need to operate autonomously for longer periods, which requires onboard energy generation, storage capabilities and efficient software-hardware interaction. Additionally, to support fleet-based operations, distributed computing systems are needed.

Technology Needs:

- **Onboard energy generation and storage**: Develop efficient energy systems that enable robots to operate for longer durations without frequent recharging or maintenance. This involves innovations in energy storage technologies, as well as new ways to generate energy from the environment (e.g., through solar or kinetic energy harvesting).
- **Onboard computing capacity**: Develop high-performance computing systems for real-time data processing. AI accelerators and specialized hardware are essential for handling complex tasks such as perception, reasoning, and planning in real- time. This includes advancing chip technology and system architectures to improve energy efficiency and performance, and co-optimizing hardware and software. Hybrid GPU-CPU architectures, scaled down wafer neuromorphic processors, event-based processing platforms and real-time low latency computing are interesting avenues that must be co-optimized with robotics platforms.
- **Near edge computing and AI accelerators**: AI-powered robots require edge computing solutions that enable real-time data processing closer to the source of data. The development of specialized AI accelerators for near-edge computing will support the complex workloads required for robotics applications, in particular for incremental learning of robotic fleets once they are deployed.
- **Networked HPC and complete edge-to-cloud frameworks for fleet learning**: the deployment of AI-powered robot fleets will require significant computing resources that will not be easy to meet with single-cluster HPC paradigms. Developing the technological frameworks to allow learning on networked HPC infrastructures, as well as allowing for seamless computing resource

allocation at different levels (edge-to-cloud) will be key to ensure efficient, frugal learning and incorporation of real-world data for entire robot fleets.

Autonomy and Adaptability

Key challenge: To operate autonomously in dynamic and unstructured environments, robots need advanced sensing, reasoning, and decision-making capabilities. The use of world models, already useful for virtual reinforcement learning, is also an interesting avenue to develop new reliable supervision and complex tax and motion planning.

Technology Needs:

- **Sensor fusion and semantic mapping**: Advanced multi-modal fusion algorithms are needed to combine data from various sensors (e.g., cameras, LiDAR, tactile sensors, as well as new sensors to enhance multimodality) to construct accurate real-time world models. These models enable robots to understand and interact with their environment, which is critical for safe and effective autonomy.
- **Knowledge management and modeling**: longer-term deployment of AI-powered robots will require them to receive different types of information over time. The way in which robots process and manage this information, and transform it into actionable models, still requires significant efforts. These efforts should be directed towards the development of modules that will enable life-long learning[14], critical for long-term deployments in changing environments.
- **Situational awareness and scenario prediction**: Robots must be able to predict and plan for future scenarios in structured and unstructured environments, including potential risks and opportunities. This requires integrating digital twins (DTs) for scenario simulation and combining symbolic reasoning with machine learning to enhance decision-making in dynamic settings. AI can contribute decisively to the generation of future scenarios during the process. Situational awareness also extends to social situational awareness (see below).
- **Long-term planning and task prioritization**: Robots must be able to plan over extended periods, dynamically adjusting to changing environments. This requires advanced algorithms that can balance short-term task execution with long-term planning while optimizing resources.
- **Coordination**: AI-powered robotics solutions will rarely work in isolation. The technologies necessary for collaborative missions in uncertain, structured environments (up to and including swarm intelligence) are critical to achieve solutions that are effective on the field.

Safety and Security

Key challenge: Ensuring the safety and security of AI-powered robots is paramount, particularly in environments where robots interact with humans.

Technology Needs:

- **Safe/soft actuation**: The development of soft robotics and safe actuation methods is critical to ensuring that robots can interact physically with humans and sensitive environments without causing harm to either of them.

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- **Trustworthy AI**: AI-powered robots must operate in a way that is understandable and predictable to humans. This includes the development of hybrid AI stacks incorporating explainable AI methods or other means ensuring that robot decision- making is reliable and transparent, which is essential for building trust and ensuring safety, but also advancing robotics-specific trustworthy data and AI pipelines.
- **Cybersecurity**: As robots become more integrated into networks and infrastructure, robust cybersecurity measures are essential to protect them from malicious attacks and ensure the integrity of the data they generate and process.

Social Adaptation and Human-Robot Interaction (HRI)

Key challenge: For AI-powered robots to be successfully deployed in human-centered environments, they must be socially adaptable and capable of interacting safely and naturally with humans.

Technology Needs:

- **Natural human-machine interaction**: The development of intuitive and user- friendly interfaces, including natural language processing (NLP) and gesture recognition, will enable robots to interact more effectively with humans. To be effective, both technologies should be adapted to the language and cultural diversity found across Europe. The technology should extend to social situational awareness, helping robots to enact mutual recognition with humans, other beings and robots, as well as manage their roles and read complex situations with a social dimension.
- **Human-robot collaboration**: AI-powered robots must be able to collaborate with humans in shared spaces. This requires robots to understand human intentions, adapt to the context of interactions, and provide real-time feedback.
- **Trustworthy AI**: AI models for robotics must be designed to operate ethically, respecting human autonomy and privacy. This includes ensuring that robots exhibit empathy, respect for social norms, and safety during interactions.

Virtual Learning and Real-World Adaptation

Key challenge: Robots must continuously learn and adapt to new environments and tasks, including scenarios that were not foreseen during their initial programming.

Technology Needs:

- **Virtual learning environments**: The development of realistic simulation platforms will allow robots to learn and refine their skills in safe, controlled environments. These systems must bridge the simulation-real gap by synchronizing real-world data with virtual models. Overcoming the sim-to-real gap is critical for the virtual learning to be effective upon deployment in the real-world[15].
- **Reinforcement learning for whole-body motion control**: Reinforcement learning (RL) algorithms enable robots to learn autonomously from their

15 Billard, Aude et al. « Will AI alone solve robotics? » - in preparation

experiences. However, these algorithms must be optimized to be data-efficient and capable of transferring learned behaviors from virtual to real environments. The integration of reinforcement learning into wider hybrid AI architectures in a safe, reliable manner remains a challenge.

- **Imitation learning**: the development of multimodal approaches for imitation learning from humans, and the integration of these approaches into overall hybrid AI architectures is also a promising avenue to accelerate the capabilities of AI- powered robotics solutions.
- **Distributed learning**: As robots work in fleets, distributed learning systems will allow them to share knowledge and improve collectively. This involves developing frameworks that enable decentralized learning while preserving privacy and ensuring security.

Modularity and Flexibility

Key challenge: The increasing complexity of robotic systems demands flexible and modular designs that can easily adapt to various applications.

Technology Needs:

- **Modular robot design**: Robots should be designed with interchangeable parts and components that can be easily customized to suit different tasks and environments. This requires advances in materials science and the development of modular, scalable robotic platforms.
- **Low-code/no-code programming**: As the complexity of robotics systems grows, low-code and no-code programming tools will be crucial for enabling non-expert users to deploy robotic systems. This will facilitate faster adaptation of robots to diverse use cases.

Conclusion

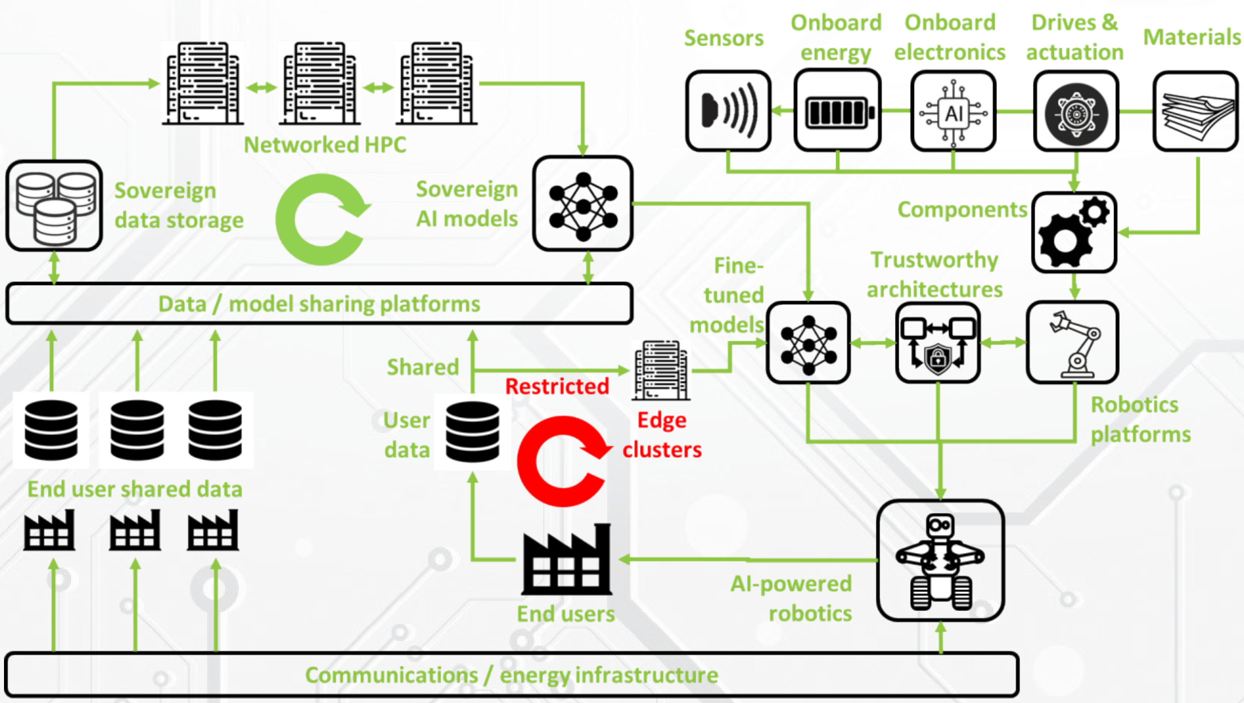
To meet the growing demands of AI-powered robotics, Europe must prioritize these technological advancements across energy, computing, autonomy, safety, and human-robot interaction. By addressing these challenges, Europe can position itself as a global leader in robotics innovation, ensuring that its solutions are not only cutting-edge but also aligned with European values of safety, sustainability, trust, and sovereignty. The development of these technologies will form the backbone of a vibrant, sustainable, and ethical robotics ecosystem, but the way in which the technologies are developed and matured into new components and solutions, the way in which new ventures are created and technology is transferred, as well as other underlying success factors, are just as critical as the technologies themselves. We will cover these factors in the next chapter.

5. Bringing AI-powered robotics to market

We have seen that significant advances in technology are still necessary to make the widespread deployment of AI-powered robots a reality. However, the challenge is not just technological: we need to translate science and technology into scalable, deployable solutions that generate value. The urgency is compounded by the aggressive strategies being pursued by both the United States and China, which are making significant strides in deploying general- purpose AI-powered humanoid robots, autonomous mobility solutions, and other robotics technologies. These initiatives are supported by bold, high-risk investments, regulatory agility, and unified markets that Europe does not yet enjoy.

For Europe to gain and maintain a competitive edge, we must not only build on our existing scientific and technological strengths but also address the critical gaps in transforming these innovations into solutions that can thrive in the market. This chapter outlines the steps necessary for Europe to overcome these barriers, accelerate the transfer of R&D to industry, and create the regulatory and economic conditions that will allow AI-powered robots to reach their full potential across key sectors.

The following image gives an overview of the complexity of the ecosystem that must be reinforced and developed. On the right side, we find the existing robotics industrial value chain, which needs to be reinforced and supported to participate in the R&D efforts and become an integral part of the AI-powered robotics ecosystem. The existing industrial AI ecosystem will need similar actions to adapt to the new data volumes and sharing paradigms, including the industrialization of the anonymization and security pipeline to foster data sharing by end users. Action is needed across the board to reinforce existing actors, develop new ones, and equip them with sovereign technologies and tools.



Accelerating the Transfer of R&D to Industry

The gap between cutting-edge research and real-world deployment remains a significant challenge in Europe's robotics landscape. This gap has resulted in fragmented efforts and delays in the commercialization of new robotics technologies. Europe must foster stronger innovation ecosystems and provide targeted funding mechanisms that can turn research into scalable, deployable products. This will involve bringing together the fragmented parts of the ecosystem and aligning them with strategic objectives.

a. Strengthening Innovation Ecosystems

Challenge: The disconnect between academic research and industrial application is still a major issue. Europe has world-leading research, but there is often insufficient coordination between academia, industry, and government bodies to drive real-world applications.

Actions:

- **Foster Collaborative Innovation**: Establish collaborative innovation ecosystems where academia, startups, SMEs, and established companies work together to accelerate commercialization. This includes technology transfer offices, incubators, and public- private partnerships that can bring new ideas from research to market more quickly. It is possible that the ecosystem-building dimension of current European-funded mechanisms might have to be sacrificed to move fast in cases where the direction is clear. However, existing initiatives such as the Testing and Experimentation Facility (TEF) network can be useful to assist in the creation of datasets, validate new models and architectures in realistic settings, and accelerate the diffusion of new technologies. European Digital Innovation Hubs (EDIH) can also play a role in the latter, engaging European SMEs into Data Space initiatives, and exposing them to emerging sovereign AI-powered robotics solutions.
- **Focus on Flagship Technology Initiatives**: Support large-scale research and development initiatives for critical components for AI-powered robotics, such as:
  - Human-friendly, high-performance actuation systems
  - Hybrid AI technologies for reliable task and motion planning
  - Embedded low-consumption electronics and hardware for energy efficiency, co-optimizing AI software and hardware
  - Federated computing infrastructures for developing AI models incrementally
- **Public-Private Partnerships**: Mobilize both public and private sector funding to create joint projects that integrate cutting-edge R&D with industrial needs, ensuring technology is tested and refined in real-world settings.

b. Targeted Funding Mechanisms

Challenge: Traditional venture capital does not always support the high-risk, long-term nature of robotics development.

Actions:

- **Challenge-driven Funding**: Create a series of large-scale, challenge-driven funding initiatives—similar to the DARPA model—that encourage a competitive environment for teams working on high-impact robotics applications. The proposed funding range of €25-50 million per project within each challenge is necessary to achieve meaningful progress even in short-term challenges. The possibility of launching large-scale targeted projects for long-term applications should also be considered.

- **Post-challenge Financing**: Once successful prototypes are demonstrated, provide additional financing to help bring them to market as fully functional, scalable solutions.
- **Venture Funds for Robotics**: Establish specific venture funds tailored to the unique economic and time constraints of robotics companies. These funds would help bridge the gap between early-stage R&D and the commercialization of prototypes, particularly for startups and spinoffs.

Overcoming Industry Ecosystem Fragmentation

Europe's robotics industry is fragmented across different sectors and technological areas. This lack of coordination between research, technology developers, and end-users creates inefficiencies and slows down the commercialization of new solutions. Addressing this fragmentation is essential for unlocking the full potential of AI-powered robotics.

a. Fostering Cross-Sector Collaboration

Challenge: The value chain for robotics—comprising hardware, AI, energy, and materials—is often fragmented, with individual players focusing on isolated components, which slows down the development of comprehensive, integrated solutions.

Actions:

- **Cross-Sector R&D Projects**: Promote cross-sector R&D initiatives that encourage collaboration across industries such as healthcare, agriculture, manufacturing, and logistics. By uniting stakeholders from various sectors, Europe can develop holistic solutions to meet common challenges, and in particular create the necessary markets for new components and technologies
- **Integrated Testing Platforms**: Invest in integrated platforms where new robotics technologies—spanning hardware, AI algorithms, and energy systems—can be tested together. This approach will allow for better integration of components into functioning, real-world systems.
- **Creating Synergies in Value Chains**: Support collaboration along the robotics value chain, from OEMs (original equipment manufacturers) to hardware suppliers, software developers, and end-users, ensuring that innovations flow seamlessly from research to industry applications.

b. Harmonizing Regulatory and Certification Frameworks

Challenge: Regulatory barriers and difficulties to deploy accreditation and auditing mechanisms for the safe implementation of AI slow down the deployment of AI-powered robotics. A lack of alignment between European regulations and those in other global regions adds to the challenge.

Actions:

- **Regulatory Harmonization**: Robustify the unified regulatory framework for AI and robotics across the EU, streamlining the approval and accreditation processes for new technologies and ensuring that European robots meet high safety, reliability, and interoperability standards.

- **Regulatory Sandboxes**: Establish regulatory sandboxes in key sectors such as healthcare, agriculture, and mobility, where new AI-powered robots can be tested in real-world environments. These sandboxes will allow for rapid experimentation while ensuring that public safety and ethical considerations are maintained.
- **Global Alignment**: Work with international regulatory bodies to align European standards with global best practices, ensuring that European robots can compete in global markets without encountering additional barriers.

Moving Different Technology Roadmaps Together

Developing AI-powered robots requires the integration of advances in multiple areas, including AI, robotics, energy storage, and materials science. However, these technological areas often progress at different rates, creating bottlenecks in development and deployment.

a. Cross-Disciplinary Collaboration

Challenge: Progress in one technology area may outpace development in others, particularly with AI advancements moving faster than the corresponding hardware and energy systems.

Actions:

- **Cross-Disciplinary Research**: Encourage collaboration between researchers in robotics, AI, materials science, energy systems, and computing to ensure that advancements in each field are aligned. In addition, collaboration should be extended to social and human sciences in cases where the robots will operate in human environments.
- **Integrated Development**: Focus on integrated development where hardware, AI, and software systems are co-optimized from the start to ensure seamless operation in real- world environments.

b. Modularity and Scalability

Challenge: AI-powered robots need to be adaptable to a wide range of industries and applications. However, many existing robots are overly specialized, limiting their ability to scale across sectors.

Actions:

- **Modular Robots**: Prioritize the development of modular robots that can be customized for different applications in industries like healthcare, agriculture, and manufacturing.
- **Open-Source Platforms**: Promote open-source platforms that allow for the modular assembly of AI-powered robots and encourage collaboration between various stakeholders.

Ensuring Robust Industry Adoption

For AI-powered robots to be widely adopted, both industries and societies must be prepared for their integration. This includes preparing the workforce, addressing societal concerns, and ensuring public trust in these technologies.

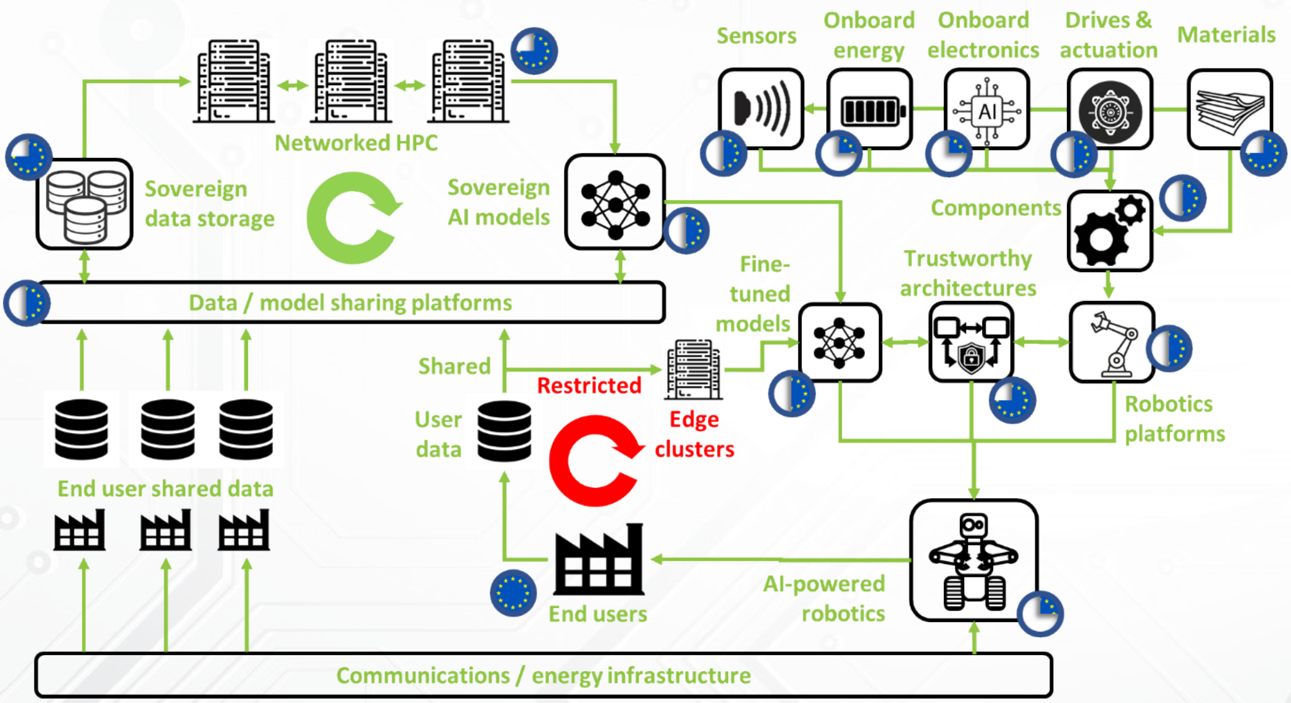
a. Preparing the Workforce for Robotics

Challenge: There is a significant skills gap in AI and robotics, with not enough workers trained to develop, operate, and collaborate with advanced robotics systems. **Actions**:

- **Education and Training**: Expand robotics and AI programs in European universities, vocational schools, and research institutes to ensure a steady pipeline of skilled workers.
- **Reskilling Programs**: Create reskilling and lifelong learning initiatives that help workers from impacted industry sectors transition into roles that involve working with robots and AI technologies.

Key Recommendations for Strengthening Europe's Robotics Ecosystem

The actions that we have described must be honed and fine-tuned to fill gaps and overcome barriers for deployment. An initial qualitative analysis of the existing capabilities in the ecosystem shows both European strengths (e.g. industrial end users, trustworthy AI architectures, drives, materials, sensors…) and areas that need support for the right players to emerge and scale:



The actions listed in the previous chapter must therefore be tailored to take into account the heterogeneous situation of both in the value chain and per industry sector. In general terms, the following actions warrant a specific focus:

1. Technology Flagships:

A number of ambitious technology development programs will be necessary to develop differentiating technologies in the areas where key challenges still exist. To build world- leading capabilities in AI-powered robotics, Europe must invest in technologies that address foundational bottlenecks and enable a new generation of human-centric, sustainable, and high-performance robotic systems. This includes not only robotics-specific innovations but also critical supporting technologies such as energy-efficient electronics, material science, and computing infrastructures tailored for distributed, hybrid AI systems.

Areas such as human-ready safe actuation, hybrid AI frameworks, embedded electronics, federated learning technologies for robotic fleets are all examples of areas where ambitious initiatives are required.

These technology flagship initiatives should designed to overcome current limitations, create opportunities for the emergence of new industrial players, and secure Europe's technological sovereignty across a wide range of enabling domains.

Implementation Mechanism

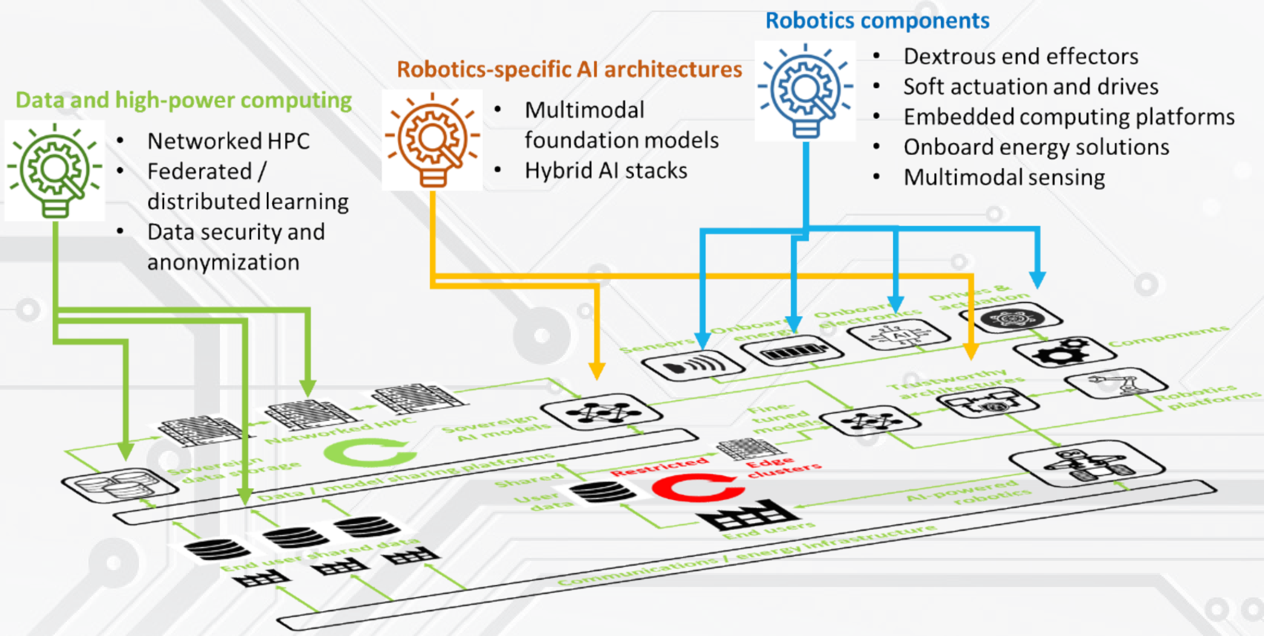
Each flagship initiative will run over 3 to 5 years, depending on the specifities of the technology it targets. It will bring together academic consortia with one or more industry partners. In areas where no suitable industrial partner currently exists, the initiative will encourage new industrial ventures to emerge.

Funding per flagship initiative will range from €20 to €50 million, with a total flagship envelope of €1–2 billion. Deliverables will include:

- **Functional** technology demonstrators
- **Avenues for** exploitation of the technology, which should contemplate the transfer to existing actors or the creation of new ventures as appropriate
- Detailed recommendations for regulatory and standardization efforts

Technology Priorities

The following figure illustrates with examples how flagship initiatives will feed into the AI- powered robotics ecosystem. The list of flagships must be refined and prioritized further, but should include actions aimed at improving robotics components and platforms, as well as the underlying infrastructure needed for AI-powered robotics.



Supporting Technologies:

- **Electric motors and drives**: focus on performance, cost, energy consumption, and substitution of rare or imported materials.
- **Advanced materials and physical architectures**: development and modeling of soft and multi-material robotic structures, with an emphasis on circular economy, bio- sourced materials, degradability, and supply chain sovereignty.
- **Energy systems**: efficient storage and charging solutions tailored in particular to long- term deployment, e.g. for agricultural and environmental robots.
- **Next-generation electronics:**
  - Onboard processors optimized for generative AI learning and inference.
  - Federated edge-cloud architectures for training and deploying robot fleet intelligence.
  - Electronic skins to enable proprioception and safe, nuanced interaction.
  - Wearable human sensors to facilitate collaboration in harsh or uncertain environments.

Robotics Technologies:

- **Trustworthy AI components:**
  - Transparent, open full-stack architectures
  - Hypervision systems for hybrid planning and situational awareness
  - Out-of-distribution detection and operational design domain (ODD) supervisors
  - Embedded predictive simulations for real-time decision-making
  - Platforms for reliable distributed learning and large scale fleet deployment
- **Planning and Control:**
  - Hybrid AI for dynamic task planning
  - Whole-body motion control
  - Symbolic-motion integration through knowledge-based planning
  - Robust semantic models to bridge the sim-to-real gap
  - Manipulation of deformable objects
  - Controllers for soft robotics
  - Long-term planning and navigation under uncertainty
  - Multimodal locomotion in natural terrain
  - Human-robot co-planning frameworks
  - Reliable control of robotics swarms
- **Human-Robot Interaction:**
  - Social behavior models for robots in shared spaces
  - Multimodal interfaces blending voice, gesture, and gaze, adapted to cluttered and dynamic environments
  - No-code programming frameworks

- **Robotics applications design:**
  - Extended generative design frameworks leveraging AI to accelerate the deployment of new robotics solutions.

2. Challenge approach

To foster rapid, application-driven innovation, we propose a Challenge Approach centered on ambitious, time-bound, and competitive projects targeting priority application areas. These challenges will push the frontiers of robotics integration in high-impact domains, de-risk investments, and facilitate the emergence of new robotic startups. The approach can be inspired from successful initiatives such as DARPA challenges or the ARGOS challenge in France.

Challenge Framework

Each challenge will last 6 to 12 months, executed by multi-partner consortia involving academic and industrial actors. Where appropriate, new industrial players will be seeded at the end of this process (see following section).

Challenges will be designed in co-opetition mode (cooperation and competition) and defined in consultation with public authorities, industry stakeholders, and researchers.

Each challenge will receive up to €50 million, with the overall challenge funding amounting to €2.5 billion over the full strategy period.

Priority Areas and Expected Results

Nine application areas will be prioritized, with up to five challenge cycles per area as new technologies become available and push the boundaries of the respective domains. The challenges should cover the priority areas that we have specified, and their sequencing should be determined by a combination of technological maturity, potential for market impact and capacity building potential for the European ecosystem.

Each challenge will deliver:

- A validated robotics application demonstrator
- A gap analysis identifying unresolved technical issues
- An exploitation plan to bring the resulting solution to market

Improve Robotics-Specific Risk-Taking and Capital Flow

The successful deployment of AI-powered robotics in Europe hinges on the ability to bridge persistent gaps between early-stage research, application-oriented demonstrators, and full market readiness. While Europe is a leader in foundational research, structural barriers continue to limit the transition of robotics technologies to scalable, commercially viable solutions. Addressing these barriers requires coordinated investment mechanisms, new fiscal incentives, and a rethinking of how capital is deployed across the entire innovation lifecycle.

Bridging the post-Challenge gap: from demonstrator to deployable product

Application challenges—structured programs that fund rapid development in targeted sectors—represent a crucial driver of innovation. However, without a dedicated mechanism to carry successful challenge outcomes through to certification, industrial integration, and market deployment, most solutions fail to transition beyond proof-of-concept.

Each application domain (e.g., healthcare, agriculture, manufacturing) requires differentiated levels of support based on its technological and regulatory complexity. For instance:

- Healthcare robotics require certification, clinical testing, and extensive safety validation.
- Agricultural robotics demand investment in energy storage, edge computing, and reliable low-latency communications in remote environments.
- Manufacturing benefits from integration pathways through existing industrial partners but still requires domain-specific validation and safety mechanisms.

The pathway from demonstration to market requires not only capital, but sector-specific expertise and trusted intermediaries to validate, scale, and integrate the technologies. This is especially critical in sectors with fewer large incumbent integrators.

To address this, Europe should implement a Post-Challenge Transition Fund—targeting projects emerging from flagship initiatives and sectoral challenges. This fund would offer medium-term (2–3 years) support to cover pre-certification, integration, and commercialization, with conditional follow-on support based on progress milestones.

Closing the capital gap to overcome Europe's robotics investment deficit

Europe continues to face a structural deficit in venture capital funding for scale-ups, particularly in deep tech and robotics:

- U.S. investors fund 42% of EU startups, with multiple examples of European robotics ventures scaling via American funds.
- Median Series A rounds in Europe are 40% smaller than in the U.S.
- Europe accounts for only 5% of global venture capital, compared to 52% in the U.S.

Examples of European robotics startups like 1X and Neura underscore the challenges: despite strong technical foundations and early European investment, these companies rely on non-European capital for scaling.

To prevent a continued outflow of robotics talent and intellectual property, Europe should adopt a dual strategy: retaining ventures and expanding from Europe.

A dedicated fund—potentially under InvestEU—should be launched to support high-potential robotics scale-ups. An indicative structure could include:

- €3.5 billion minimum funding for 20 scale-ups over 7 years (average €25 million per scale-up).
- Mixed public-private financing, with EU guarantees reducing investor risk.
- Strong alignment with post-challenge outcomes and flagship technology readiness.

Permanent robotics challenge track with scale-up path

Introduce a permanent robotics challenge stream under EIC Pathfinder (or equivalent), with:

- Increased funding levels (€25–50 million).
- Extended timeframes (up to 5 years).
- Embedded pathways to commercialization via transition-to-scale calls.

Fiscal Incentives for Robotics Investment

Offer fiscal advantages for robotics-focused EU funds, and establish tax incentives for industrial actors and family offices investing in robotics.

Infrastructure Investment Integration

Ensure robotics-specific needs (e.g. edge computing, low-latency networking, safe energy storage) are considered in all major EU infrastructure and digital programs (e.g. EuroHPC, where the consideration of robotics in emerging AI Factories is an encouraging development).

3. Develop Industrial Data Spaces

The rise of AI-powered robotics depends on access to relevant, representative, and high- quality data. However, the industrial landscape is marked by legitimate concerns over data privacy, competitiveness, and sovereignty. To unlock the full potential of AI systems— particularly those using large foundation models—a new paradigm must emerge: one that enables progressive, secure data sharing while giving control back to the data holders :

- Foster the sharing of anonymized or non-sensitive data to support large-scale pretraining of foundational AI models for robotics.
- Enable fine-tuning of smaller models at the edge using context-specific, retained data under full control of local actors.
- Strengthen European industrial sovereignty through the development of a secure, trusted data ecosystem and enabling pipeline actors.

To overcome the trust barriers currently blocking industrial data sharing, Europe must promote a **two-tiered data strategy**:

- **Tier 1: Foundational Sharing** – Public and industry actors contribute non-critical, anonymized, or synthetic datasets to pretrain general-purpose models.
- **Tier 2: Sovereign Fine-Tuning** – Organizations retain valuable proprietary data to fine- tune or adapt models at smaller scale, close to operations, with no requirement to share it.

This model respects European values of sovereignty, decentralization, and trust by design.

Supporting Mechanisms

- **Trusted data intermediaries**: Create certified third-party entities to host and govern sector-specific data exchanges.
- **Data pipeline actors**: Incentivize the emergence of SMEs specialized in curation,anonymization, synthetic generation, and compliance-as-a-service.
- **Participation by TEFs**: Ensure that Testing and Experimentation Facilities contribute validated datasets and facilitate sectoral data space expansion.

- **Project-driven dataspace growth**: Require EU-funded projects to create or expand data spaces aligned with their domain and reusability goals.

Optimize regulatory frameworks

Europe's regulatory ambition must ensure that innovation in AI-powered robotics proceeds with safety, transparency, and societal acceptance. Yet, rigid or premature frameworks can stifle early-stage experimentation and hinder global competitiveness. We must accelerate innovation through sandboxes and experimentation while embedding compliance by design in robotic systems and organizations:

- Enable learning loops between innovation and regulation through experimentation.
- Integrate regulatory feedback mechanisms into flagship technology and application challenge projects.
- Reinforce Europe's position as a global standard-setter through ethically grounded and operationally agile frameworks.

Compliance-through-testing approaches, built on feedback loops between regulatory actors and innovation projects, should be explored. This implies:

- Regulatory sandboxes embedded in strategic sectors (e.g., healthcare, manufacturing, agriculture).
- TEFs tasked with regulatory impact assessments when validating new technologies, feeding into the evolution of guidelines and standards.
- Promotion of AI Act compliance via sovereign technical pathways, enabling trustworthy, certifiable robotic solutions.

Key Actions

- Consolidate and expand regulatory sandboxes, building on national experiments (e.g. Spain)
- Mandate TEFs to assess regulatory readiness and provide pre-certification services.
- Establish direct interfaces between TEFs and EU-level regulators, including data protection authorities, safety agencies, and standards bodies.
- Develop a compliance maturity model for AI-powered robotics, enabling progressive adoption based on risk and deployment stage.

Regulatory governance should remain anchored in EU institutions, with strong Member State participation for subsidiarity and adaptation to national contexts.

6. Conclusions

This strategy document outlines an ambitious path for Europe to lead the development and deployment of AI-powered robotics. At this pivotal moment, Europe faces not just an opportunity but a profound responsibility to chart a unique course that reflects our values, strengths, and vision for the future.

A Call to Action for a Unified European Vision

The challenges ahead—demographic shifts, environmental sustainability, economic resilience—demand immediate and decisive action. Europe's fragmented markets, regulatory complexities, and fragile robotics ecosystem are hurdles we must overcome, not by mimicking global competitors, but by forging our own sustainable and value-driven path.

The roadmap highlights several critical imperatives:

1. Collaborative Innovation for a Unified Ecosystem:

Europe must break down silos across sectors—AI, robotics, materials, energy, and beyond—to foster an ecosystem that integrates all technological components seamlessly. The co-optimization of hardware and software must become a cornerstone of our strategy.

2. Frugal and Trustworthy Technological Breakthroughs:

Europe must lead in developing energy-efficient, adaptable, and frugal robotics solutions, ensuring these technologies align with European values of safety, trust, and strategic sovereignty.

3. Overcoming Fragmentation for Global Impact:

Harmonized funding mechanisms and cross-border collaboration are non-negotiable for scaling robotics solutions effectively. By uniting as a single market, Europe can unleash its full potential and stand as a global leader.

4. Accelerating Market Readiness:

Transforming research breakthroughs into commercial success stories is essential. Europe must invest in robust innovation ecosystems, enhance access to capital, and adopt a challenge-based approach to fast-track high-impact robotics solutions.

5. A People-Centric Transformation:

As robotics redefine industries, Europe must prioritize the workforce by investing in education, reskilling and lifelong learning initiatives. This ensures that technological progress uplifts society rather than leaving segments behind.

6. Global Leadership in Ethical AI and Regulation:

Europe's commitment to human-centric AI and ethical standards positions it uniquely to lead the world in responsible robotics deployment. Setting global benchmarks in regulation and trust will be a defining advantage.

Envisioning the Future

The journey towards a European AI-powered robotics paradigm is not merely about technological advancement; it is about redefining how technology – and the digital tapestry we are weaving around our physical reality – serve humanity. From manufacturing and healthcare to agriculture, mobility, security and urban infrastructure, robotics must become a force for sustainability, economic resilience, and social well-being.

In a world grappling with finite resources, Europe can exemplify how innovation and sustainability go hand in hand. By focusing on energy-efficient robotics, leveraging industrial data, and building sovereign, sustainable AI solutions, Europe will establish a paradigm that is not only competitive but indispensable in addressing the world's toughest challenges.

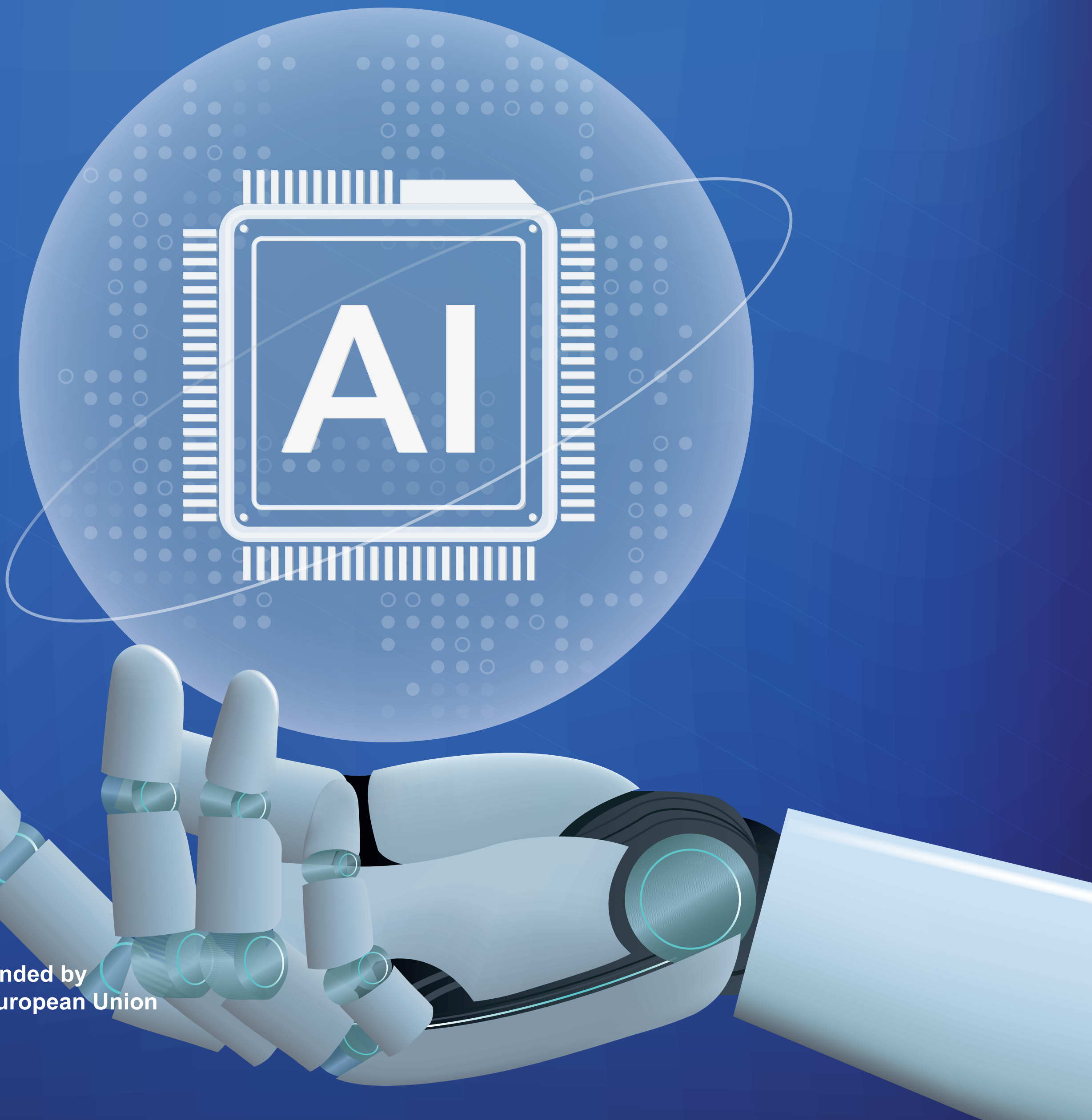
Seizing the Opportunity

The alternative to this vision—a fragmented, reactive Europe—risks not only economic stagnation but the loss of our sovereignty, values, and global relevance. The stakes could not be higher, and the time to act is now.

By committing to unprecedented cooperation across member states, industries, and academia, Europe can transform its current challenges into historic opportunities. Together, we can build an AI-powered robotics ecosystem that safeguards our values, uplifts our society, and secures Europe's place as a global leader for generations to come.

The AI Data Robotics Association

adr-association.eu



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