The AI Data Robotics Association

Policy paper and Technology Roadmap GenAI and Robotics 4EU

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Executive summary

This policy paper and its technology roadmap aim to provide insights into these strategically important technologies. It responds to a request from the European Commission and the results from collaborative efforts among key stakeholders in artificial intelligence, robotics and data across research and industry, coordinated by the AI, Data and Robotics Association (Adra).

Generative Artificial Intelligence (GenAI) and Robotics, both advanced "general purpose technologies", find themselves at a point of convergence, giving them the potential to demonstrate unprecedented capabilities that can disrupt markets and redefine the limits of what is possible by combining physical action and perception, cognitive prowess and adaptability.

GenAI empowers Robotics and Robotics empowers GenAI. Thanks to robots' unique capabilities in action and perception, GenAI can explore and interact with the physical world. AI researchers see in robotics the potential to overcome the current limits of AI, and to move towards general intelligence thanks to embodied AI, which offers a holistic problem-solving model. Thanks to GenAI, robots can get a better understanding of their environment, interact in a natural way with people, and efficiently perform new tasks they haven't been trained for. New robots can also be designed in response to predefined criteria.

This implies advancements in the technological components of GenAI and Robotics, which may include conception and design, multimodal perception and cognition, control systems for adaptation to complexity, simulations of the physical world, human-robot interaction, robot-robot interaction, localisation, mapping, navigation, and foundation models on 3D objects. Focusing on robotics, it is essential to research and develop new mechatronics components and versatile robotics platforms.

A significant divide exists between industrial end-users, who are eagerly awaiting mature AI solutions but feel unequipped to implement them, and the vast community of researchers, technologists and equipment manufacturers, who are often disconnected from the end-users' realities. This disconnect hinders the development and deployment of advanced AI and robotics solutions. As the ultimate mediators in the value chain, integrators play a pivotal role in bridging this gap by channelling innovations and new developments from research to industry.

Consequently, dedicated programmes should be established to support pioneering integrators, operational pilot lines, and the upskilling and scaling-up of territorial integrators. These integrators are essential in providing a competitive and sustainable edge to our SMEs, deploying our technologies and values, and serving as crucial stakeholders in advancing circularity.

There are use cases in almost all strategic industrial ecosystems: Manufacturing & Engineering, Logistics and Laboratory Automation, Inspection & Maintenance, Agriculture & Agrifood, Social Robotics: Assistive Robots & Healthcare, Security, Defence and Public Services, Construction, Hospitality and Retail, Biotechnologies, Medical, Aerospace and others. However, the convergence of GenAI and Robotics brings critical challenges that must be addressed. These include safety, explainability and reliability, cybersecurity, embodiment and real-time interaction, sustainability beyond energy efficiency, and alignment with European values.

Europe needs to seize the opportunity presented by combining these general purpose technologies. It should avoid entering the race on the same terms as the USA and China, which rely on mass investment, big data and immense compute power, but should define its objectives by taking into account its strengths, weaknesses and cultural and societal values, charting its own path towards the convergence of GenAI and Robotics.

In conclusion, the convergence of GenAI and Robotics opens up vast new possibilities, highlighting the critical role of Robotics in fully unlocking GenAI's transformative potential. It is imperative to sustain investment in European GenAI, focusing on establishing robust data frameworks and fostering the development of safe, trustworthy, ethical and frugal European foundation models that reflect our culture and values.

Key Recommendations

1. **A Blue Ocean strategy for Europe.** Investigate the benefits of adopting a "Blue Ocean" strategy, that spurs innovation, technological advancement and economic impact that responds to social and sustainable goals and values. Such an approach favours technology transfer into actual business applications and opens up novel solutions in currently inaccessible markets.
2. **Educate, Train and Retain Talents.** Special focus should be placed on scaling education and training for the tech community, building resilient high-performance infrastructure for computation, data, and connectivity, and developing open-source software for community building and sovereignty. Further, we need to articulate strategies in this field and develop policies and standards that foster innovation.
3. **Build up a Resilient and High-Performance Infrastructure for Computation, Data, Connectivity.** This can be achieved by establishing resilient infrastructure for computation and for data, which is capable of addressing future needs.
4. **Adopt a Fully Integrated Approach across the whole technology stack.** The value chain for GenAI and Robotics is complex, encompassing both hardware and software. Each segment and sub-segment of this chain represents a market on its own, yet is inextricably linked to the others. In order to tackle this increasing complexity and make AI sustainable, these two domains need to be more strongly integrated.
5. **Drive advancement in mechatronics.** Robots are required to interact with their surroundings to execute tasks. A robot driven by GenAI will be able to make decisions on how to navigate, manipulate and operate in unplanned situations and unstructured environments. It is therefore essential that a robot is not only cognitively able to perform the tasks but also possesses the physical capability to interact with a variety of tasks. This will require continuous support for advancements in mechatronics.
6. **Explore Novel AI approaches.** While Europe must leverage GenAI to its fullest potential, significant efforts should be made to explore novel AI approaches, particularly those offering improvements in explainability, data and energy efficiency. These emerging AI technologies hold immense promise for bolstering technological sovereignty and European leadership within the field.
7. **Open Source for Community Building, Digital Commons and Sovereignty.** Europe urgently needs to develop state-of-the-art technologies and to learn how to continuously and rapidly bring new AI and Robotics technologies into commercial, public, and industrial use. This means promoting the production of digital commons for AI embodiment and large action models, including datasets, challenges, models and software development platforms with genAI.

I. Introduction

This document provides insights into the convergence between Generative Artificial Intelligence (GenAI) and Robotics, technologies of strategic importance for the European economy and society. It responds to a request from the European Commission and results from collaborative efforts among key stakeholders in artificial intelligence, robotics and data across research and industry, coordinated by the AI, Data and Robotics Association (Adra).

GenAI and Robotics are "general purpose technologies" with an impact similar to that of the steam engine, electricity and the internet"[1]: GenAI questions numerous technological roadmaps and disrupts sectors at an unprecedented pace.

One of the most powerful combinations of GenAI is with robotics, which opens the door into the real world. On the one hand, GenAI promises to support rapid advances in robotics systems and, on the other hand, as robots bridge the gap between the virtual and the physical worlds, they are the hardware of choice for AI embodiment.

Today, the GenAI value chain is largely dominated by a few major US stakeholders, while China is in the race for global leadership and holds a dominant position in AI patents (61.1% in 2022), surpassing the United States (20.9% in 2022). Europe's technology sovereignty as well as its economic and geopolitical development and leadership are at stake. GenAI disruption is also an opportunity for Europe to provide alternatives to foreign technologies.. With our world-class research and education, talents and entrepreneurs, we can achieve not only high-performance, resource-efficient and resilient GenAI and Robotics technologies, but also solutions that operate respectfully with our values, culture, and the environment.

By urgently investing in these highly strategic technologies, optimising the full value chain and proactively addressing ethical, regulatory, economical, climate and environmental considerations, Europe can position itself at the forefront of the new frontier. GenAI-empowered robotics and robotics-empowered GenAI technology, can serve as a cornerstone for Europe's technological sovereignty, and support efforts to reach its Sustainable Development Goals.[2]

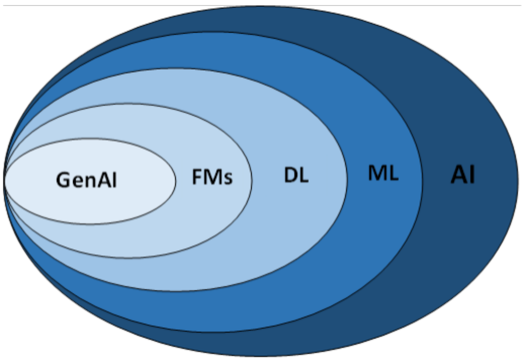
1 https://www.gartner.com/en/topics/generative-ai
2 Especially on Balanced Economic Growth, Environmental Quality, Scientific and Technological Progress, and Social Inclusion.

II. State-of-the-art

Definitions

The AI Act aligns with the OECD definition of AI systems as a "machine-based system that, for explicit or implicit objectives, infers, from the input it receives, how to generate outputs such as predictions, content, recommendations, or decisions that can influence physical or virtual environments". AI includes **Machine learning** (ML), which encompasses **Deep Learning** (DL) and also:

- **Foundation models** (FM): large, pre-trained general-purpose models that can be used for various tasks. The AI Act refers to these as to "General Purpose AI models";
- **GenAI:** generative models trained on a large amount of data in certain domains (e.g. signals, text) to generate synthetic data with similar characteristics. Task-specific, their key difference is the ability to create new content such as text, images, or videos. In this document, for the purpose of intelligibility, the term covers GenAI and foundation models relevant to robotics.



Robotics combines mechatronic systems with numerous actuators, sensors, and computers. This integration enables robots to perform manipulative tasks and adapt their mobility based on environmental changes. Examples of robots include industrial robots, surgical systems, teleoperated robots, mobile robots (for cleaning, logistics, etc.), wearable robots, humanoid robots, nano and microrobots, space robots, deep sea exploration robots or drones.

How GenAI Empowers Robotics: "Robots With Common Sense"

As they have the capability to leverage generative aspects, **foundation models** serve as the initial building blocks for developing specialised GenAI models. They are pre-trained on massive amounts of general data (models can have up to several tens of billions of parameters) for tasks such as natural language processing, the recognition and synthesis of images, sounds or human movements. They are then fine-tuned on specific tasks or datasets to better align with the desired output. By significantly reducing the effort required to develop AI components, polyvalent foundation models can help to democratise access to AI and accelerate deployment of robotics.

Foundation models are in constant evolution. In 2023, a total of 149 were released, more than double the number released in 2022. Of these, 61 originated in the US, 21 in the EU and 15 in China. The industry produced 51 notable machine learning models, while academia contributed only 15. There were also 21 notable models resulting from industry-academia collaborations in 2023, marking a new high[3].

3 AI Index Report 2024 https://aiindex.stanford.edu/report/

The integration of GenAI models is transforming robotics. Its exponential progress is paving the way for the next-generation robotic systems, because it:

- **Bridges the sim-to-real gap**: GenAI helps to make simulated environments more realistic and detailed, thereby enabling more accurate testing, training and validation of robotic systems;
- **Bridges the gap between robots and datasets**: The way we programme robots is changing. Instead of programming, we will be able to use consolidated datasets to train robots to perform tasks, including those they weren't initially trained for;
- **Bridges the robot-to-humans gap**: Advances in multi-modal generative models are improving the ability of robots to understand high-level human commands and thereby enabling more effective collaboration.

Thanks to GenAI, new possibilities open up to robots, which:

- Learn how to perform a new task from scratch much more efficiently
- by using new ways to "programme" robots by machine learning (including end-to-end learning, imitation and reinforcement learning), accelerating the pace of robotics systems integration and deployment;
- Get better understanding of the environment, including social unstructured ones
- by using GenAI to generate a semantic map, on the basis of multimodal sensors' input, to predict trajectories and behaviours giving indications on how the environment is going to evolve;
- Interact in a natural way with people and take their high-level commands
- by integrating Large Language Models (LLM) in the human-robot interaction. This has been demonstrated in a proof-of-concept stage, with the next step robustness and safety;
- Achieve tasks in swarm through robot-to-robot interactions
- by deconstructing tasks into robotic actions aligned with their skills thanks to integration of large-scale foundation models combining language, vision, 3D environment and robotic tasks;
- Perform critical tasks in social environments
- by training large action models on data gathered in actual social situations;
- Manipulate any object, including deformable, in cluttered environments
- by understanding the object's affordances and its environment;
- Be designed by GenAI
- using predefined criteria, GenAI can design the vector, components and programme of new robots and robotics systems. Significant innovations in the shape and performance of robots will profoundly transform the robotics systems & solutions.

How Robotics Empowers GenAI

GenAI turns bits into bits. Robots convert bits into physical forces. Without robots and their unique capabilities in action and perception, GenAI cannot explore and interact with the physical world. Researchers in AI are interested in robotics to overcome the current limits of artificial intelligence. The idea is to move towards general intelligence thanks to embodied AI, a holistic problem-solving model.

Thanks to robotics, GenAI can:

- Have access to real world multimodal data
- coming from various sensors and environments including industrial operations, hostile or inaccessible environments or human-robot interaction. By imposing physical limitations on GenAI systems, more responsible and frugal practices will be encouraged;
- **Investigate previously unexplored fields**
- as GenAI is provided with an entry point into the real world; deep sea and space explorations cannot happen without robotics;
- **Enable the manufacture of novel complex products**
- thanks to its versatility, robotics will become the ultimate tool capable of realising the products conceived by GenAI design;
- Develop adaptive intelligence
- due to the perceptive and action-oriented dimensions of intelligence provided by the robot. This is crucial to allow for dynamic revision of beliefs and knowledge based on experiences;
- Offer benchmarking and acceptability
- offering real-world benchmarks, robotics serves as an indicator for acceptable GenAI, enabling the verification of generated models' accuracy and enhancing operator, customer and human experience;
- GenAI embodiment also represents a necessary step on the path towards Artificial General Intelligence.

Current Technological Challenges to be Transformed into Powerful Competitive Advantage

Safety: Problems linked to hallucinations[4] of LLMs can have serious consequences, necessitating intermediate layers to ensure safety and a "safety by design" approach (i.e., inductive biases in models including physical constraints). The fact that robots operate in physical environments raises unique challenges, since a sub-optimal behaviour or interaction in the physical world may have significant consequences. Real-time processing, rapid decision-making (within 1ms) and adaptability to novel situations are critical to achieve robust robot control.

Explainability and reliability: These are especially important in robotics, which leaves no room for error. Deep learning (DL) used in this context does not yet offer the necessary guarantees and remains largely a subject of research.

Cybersecurity: Notwithstanding the fact that cybersecurity is a must in software, GenAI and Robotics might require specific cybersecurity components, as robots act in the physical world.

Embodiment and real-time interaction: The interaction with the physical environment, the real-time actions, and the need for privacy preservation, require specific energy-efficient edge compute SW & HW integrations.

4 Fluent output generated by the model but entirely unrelated to input, factually incorrect or incoherent information

Sustainability: Robot conception and design should also be environmentally sustainable, meaning that robots and robotics systems should be eco-conceived, repurpose-able, recyclable and sustainable over their complete lifecycle.

Alignment with European values: GenAI-based Robotics solutions should be human-centric, safe, trustworthy and aligned with European values.

European SWOT in GenAI and Robotics 4EU

STRENGTHS +	WEAKNESSES –
··· **Excellence of research** in mathematics, physics, AI and robotics, chip technology, high performance (HPC) and low energy consumption computer architectures. ··· Strong **entrepreneurship dynamics.** ··· EU-27 and the US have alternated as the leaders in the market for **professional service robot sales** over the past 10 years. ··· Favourable evolution of the EU market share of robotics[5] : in the last decade, Japan (35%) and the EU-27 (32%) preserved their positions as the world's **largest industrial robot sellers.** In 2022, EU market share accounted for 78% in agriculture, 44% in professional cleaning and in inspection and maintenance, 13% in medical robots and 11% in logistic systems robots. ··· Europe leads in **deep tech,** preparing for next generation innovations, e.g. quantum. ··· Europe's **5G network** supports the short latency time needed to use robots efficiently. ··· Emergence of **European middleware AI platforms** for GenAI and Robotics (e.g. Dora-rs, Pollen-vision, LeRobot). ··· **European-wide technological structures** such as AI factories, EuroHPC or digital innovation hubs.	··· **Lack of sovereignty** in chips (embedded AI), cloud and foundation models. ··· **Brain drain** to tech giants (GAFAM) & other large corporations. ··· **Start-up drain & lack of capital**: While Europe invests in AI research, it often lags behind other regions in terms of total investment, constraining the scope and scale of AI initiatives and hardware investments. ··· **Lack of follow-up actions after the Horizon project**, which funded research and innovation, to retain talent and develop IP to turn it into profitable businesses. ··· **Market fragmentation**: Europe is fragmented both in terms of strategies and markets. This hinders collaboration and innovation compared to more centralised ecosystems in the US or China. ··· Lack of access to **trustworthy data and a shortage of computing power.** ··· There are **too few foundation models** coming from Europe. ··· **Lack of articulation of technological vertical strategies** in Europe and between member states.

5 https://publications.jrc.ec.europa.eu/repository/handle/JRC132724

STRENGTHS +	WEAKNESSES −
- **European Common Data Spaces**, as unique instruments that provide controlled environments where to share and to provide high-quality industrial data in a governed, trusted and efficient way. Cross-border and cross-sector - Europe is pioneering **regulatory & legal frameworks**, including the AI Act, GRPD, Europe Digital Markets Act and its Fair, Reasonable and Non-Discriminatory principle (FRAND).	- Navigating **multiple regulations** in Europe is challenging, especially for startups.

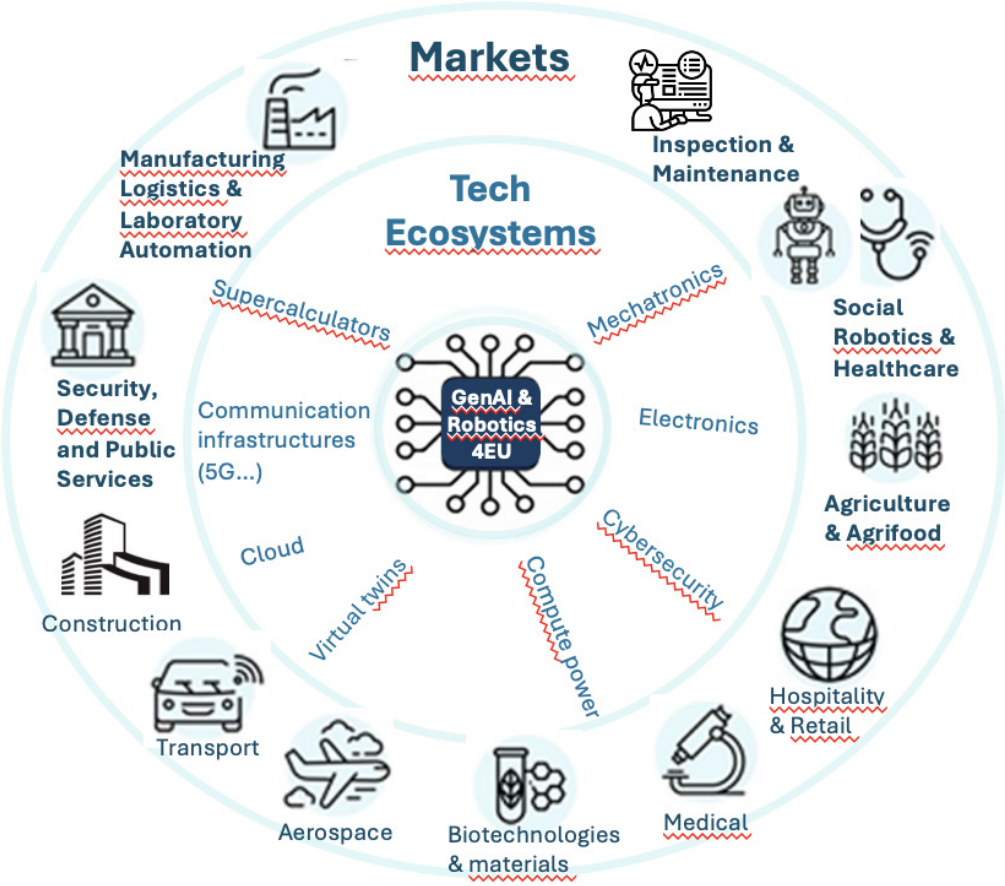
OPPORTUNITIES +	THREATS −
Convergence of GenAI and Robotics will **open new markets** with fast double-digit growth (e.g. in social robots and field robotics) and allow players to **disrupt consolidated markets with pioneering solutions.** The global market size in GenAI is projected to reach **US$36.06 billion in 2024**. With a compound annual growth rate of 46.47% between 2024 and 2028, the market is expected to reach US$356.1 billion by 2030[6]. Revenue in the global **industrial robotics market** is projected to reach **€8.52 billion (USD$9.2 billion) in 2024**, with an annual growth rate of) 2.87%between 2024 and 2028.[7] The expected **growth of service robotics markets** (CAGR 2023-2026) is: - Agriculture: +30% - Professional service robots: +38% - Professional cleaning: +50% - Inspection and maintenance: +35% - Logistic systems robots: +40% - Medical robots: +8%	Tense **geopolitical context** in key components for GenAI and robotics **Acquisitions** by major foreign technology players, due to poor alternatives in European public and private funds. The vertical integration of tech giants will lead to **strategic limitation of access to GenAI models**. Current foundation models are based on a non-European "model of the world" which implies **outputs biased** by the source culture's conventions, values and views. Current enormous **energy consumption** of foundation models, GenAI and AI in general. Energetic crisis Innovation may be inhibited through **excessive regulation** Climate change

6 https://www.statista.com/outlook/tmo/artificial-intelligence/generative-ai/worldwide
7 https://www.statista.com/outlook/tmo/robotics/industrial-robotics/worldwide?currency=EUR

III. Use cases

GenAI enables one-shot generalisation of robotic skills, which robots need to deal with open world assumptions, intuitive human-robot interaction through natural language and other modalities, and many other abilities (see the section How Robotics Empowers GenAI). If generalisation and ease-of-use are currently blocking innovation in certain robotic use cases, GenAI will have a substantial impact on making such use cases economically viable. It is also noted that GenAI raises safety and ethical concerns that have to be investigated hand-in-hand with the research and innovation effort.

AI and robotics, as general purpose technologies, have use cases in all strategic value chains:



Manufacturing & Engineering, Logistics and Laboratory Automation

Automation in manufacturing and logistics relies on controlling material handling tasks with a high degree of repeatability, at the cost of segregating robots from human environments. The result is high productivity in mundane, repeatable tasks but an inability to deal with more complex dexterous manipulation and changes or variations in objects or processes.

Augmenting industrial robots with sensors to detect collisions, vision to understand their environment, and tactile senses to prevent damage to objects and their surroundings, leads to a versatile robotic system that can interpret the required task and adapt its functions.

However, the main challenge for manufacturing, logistics and fulfilment is grasping unknown objects. It requires training on mass-collected data, but it can also be enhanced by using GenAI to augment the data, simulating new parts of scenarios or transforming 2D datasets into 3D datasets.

Thanks to GenAI, we can expect mass customisation trends and agile production lines, e.g. through automatic robot path planning generation, automatic generation of robotic work cell layouts and the automatic programming of Programmable Logic Controllers (PLCs). Robots will understand high-level human commands in natural language, which will enable accelerated deployment in SMEs, even if they lack workers skilled in robotics. Notwithstanding the need to develop versatile mechatronics actuators, GenAI robotics can boost efforts to achieve a circular economy through product dismantling, component recovery, and waste management sorting and handling.

In the **manufacturing** sector, Europe boasts a longstanding tradition of excellence. However, numerous tasks within this domain are out of the reach of "classical automation" due to their complexity and/or cost. This is particularly pronounced for low-volume, high-mix production where the business case for automating production is difficult to close due to the high investment costs of automation. Consequently, a significant portion of manufacturing operations still relies heavily on manual labour, prompting the relocation of production lines outside Europe to lower costs. The convergence of AI and robotics opens a huge opportunity for replacing manual work in the manufacturing industry with affordable automation through a new breed of safe, dexterous and intelligent robots. By leveraging these technologies, Europe can maintain or repatriate industrial production, offset a labour shortage in factories, and bolster sovereignty in industrial value creation.

Logistics flow can be improved by optimising plant layout, AMR (Autonomous Mobile Robot) fleet and traffic management from production records. Figure AI, an American robotics group, has created humanoids designed to work safely alongside humans. The company has partnered with BMW to deploy these robots in BMW's manufacturing facility in Spartanburg, South Carolina. China and the USA strongly invest in humanoid robots for the manufacturing industry.

Robots that can sense human actions, gestures and speech will enhance manufacturing and laboratories, supporting employment by allowing human-robot collaboration on tasks. However, further productivity can only be achieved by robots "understanding" human actions. With natural human-robot interactions, robots will be capable of safely moving in unstructured environments, such as retail or warehouses. Finally, robotics solutions are systems integrated in systems. In the mid- to long-term, complex GenAI & robotics systems of systems will lead to "holistic" automation solutions.

Inspection & Maintenance

GenAI and robotics provide solutions for surveillance, inspection, maintenance and repair of infrastructure in the transport sector (road, rail, maritime), energy production and distribution (oil and gas, nuclear, renewable), water supply and sanitation, communication, archaeological sites, and more.

Inspection and monitoring (I&M) operations generate vast amounts of data, even with training data that is sometimes sparse. GenAI offers the possibility to automatically analyse this data, for example, to identify infrastructure damage such as corrosion and cracks. Moreover, the demands of I&M tasks can vary significantly due to the differing geometries of infrastructure and the various tasks carried out on it (visual inspection, contact-based sensing, painting etc.). GenAI can help bridge this gap by enabling robots to understand their environment and adapt how they should operate to complete I&M mission targets.

Allowing robots to achieve higher levels of autonomy with GenAI will support their adoption in the I&M domain. This will reduce deployment time, as there will be less robot training and less human intervention needed when, for example, robots get stuck due to the unpredictability of the environment. It will also make the robots easier to operate, allowing for more intuitive human-robot interfaces and more flexible setups. For the companies producing the robots, the benefits include tailored solutions for their customers without the need to meticulously set up missions.

Agriculture & Agrifood

The European Green Deal aims to make Europe climate-neutral by 2050, boosting the economy, improving health, enhancing quality of life, caring for nature and ensuring inclusivity. Central to this plan, the Farm to Fork (F2F) strategy, seeks to create fair, healthy and environmentally-friendly food systems. Transitioning to a green and digital agrifood sector will conserve land and water, ensure safe, healthy foods andAI-driven precision agriculture will boost agrifood productivity..

Major contributions from GenAI and robotics are expected in subsectors such as arable farming, horticulture, livestock farming and food processing. (Gen)AI can be used to monitor crops and livestock, measure the ripeness of fruit and vegetables, advise farmers and support their decision-making. AI-enabled robotics reduces the need for chemical products for plant protection, as well as enabling the deployment of tools such as autonomous tractors, fruit-picking, planting machines or eventually, autonomous greenhouse production with vertical farming systems.

AI models significantly outperform traditional processing and show significant potential for processing the rapidly growing high-dimensional data collected by robots on agricultural fields for precision agriculture applications.

Unlike controlled conditions in other industries, agriculture is subject to the continuous variation of field and crop conditions. Large amounts of multi-modal data are collected on these conditions, requiring GenAI models to work with text, images and 3D sensor data. Limited internet access makes cloud infrastructure unreliable in some areas, highlighting the importance of edge AI and 5G network. Use cases show that collaboration between robotic AI agents, such as swarms of drones and robotic vehicles, is necessary.

Social Robotics: Assistive Robots & Healthcare

The intuitive natural language interactions enabled by GenAI imply a step change for the usability of assistive and service robots, and are expected in the next two years. The first applications are likely to be in domains where robots work with humans. In these cases, a human and a robot collaborate to solve tasks, and the human can correct possible erroneous GenAI interpretations, which improves overall safety and performance and makes deployment feasible.

This is the case for assistive robots for people with disabilities, where successful innovation will profoundly impact individual lives and social inclusivity. For instance, centralised teleoperation by experts keeps a human in the loop and enables the safe deployment of robots in various assistive and service applications.

The intuitive interaction and generalisation properties of GenAI will also be important for innovation in elderly care, where robots may automate specific tasks (making beds, fetching items, tidying rooms) in relatively structured environments such as care facilities. In this context, GenAI also allows completed tasks to be automatically documented, saving human caretakers from having to do so. Realising partial autonomy in combination with teleoperation will make such use cases feasible within five years.

Security, Defence and Public Services

Defence

The security situation in Europe has changed drastically in response to a high-intensity war on our continent. To become a stronger and more credible security provider, the EU has adopted a common strategic vision for EU security and defence[8]. In this vision, autonomous systems are identified as one of the disruptive and promising technologies that can provide a competitive defence edge. The European Defence Fund provides funding for these developments, supporting the increased defence budgets from the individual member states. The European Defence Industrial Strategy (EDIS)[9] also supports the production of drones. Potential synergies between civil, military and space industries need to be taken into account, including possibilities for cooperation with NATO partners.

GenAI will provide capabilities needed for robotics and (semi-) autonomous systems for defence applications. There has already been increased deployment of unmanned systems, including in the Ukraine-Russia war. These unmanned systems include aerial drones, ground vehicles, surface vessels, underwater vessels, and robots to support intelligence, surveillance, logistics, target acquisition and guided munitions. These systems are mostly operated remotely, which requires significant personnel and training. To use drones more effectively and efficiently, there is a need for more autonomous operation and teleoperation technology.Swarms of heterogeneous robots are particularly interesting in this area.

Security & Public Services

In security and safety applications, robots are often deployed when the situation is dangerous, dull or dirty. Typical applications are firefighting, rescue missions such as urban search and rescue, explosive bomb disposal, disaster response, and surveillance of critical assets. Robots can be used to assess unsafe situations, so that humans can be tasked more safely and efficiently when needed. They can also be used to manipulate objects from a safe distance, e.g. in the case of disabling an explosive. In some cases, teleoperation can be used to execute more difficult tasks; in others, especially those considered dull and repetitive, autonomy helps to reduce the human workload.

The need for autonomous technologies for defence, security and public services applications is fuelled by two developments: the changing global security situation and the scarcity of personnel in EU member states. As the number of unmanned systems is expected to increase exponentially, this need for autonomy is even more pressing.

Robots are assisting by providing situational awareness, fire support and logistics. The

8 The Strategic Compass of the European Union (strategic-compass-european-union.com)
9 https://defence-industry-space.ec.europa.eu/eu-defence-industry/edis-our-common-defence-industrial-strategy_en

environments and situations encountered in locations as diverse as agricultural plantations, battlefields, and security situations are unpredictable and constantly changing. When operating (semi-) autonomously, the robot should be able to fulfil a mission objective set by humans, and stay within the user-provided operational rules, laws and ethics boundaries. There is a need for meaningful human control – that is, control over the system's potential actions without requiring a human in-the-loop. Capabilities that are needed include:

- situation assessment (what is happening);
- navigation through the environment (how do I get somewhere?);
- manipulation of objects (how can I change this situation?);
- self-assessment (what can I do in this situation?);
- collaboration (how can I work together with the other team members?).

GenAI has the potential to improve these autonomous capabilities in the following ways:

- **Interaction**: interactions in natural language provide an intuitive interface to different users;
- **Generalisation**: the large number of examples used for training foundation models allow them to detect and interpret objects from the first encounter;
- **Planning and replanning:** GenAI can be used for planning complex missions and for replanning these missions after encountering unforeseen situations. Adding the properties of the drone in the prompting will restrict the potential outcomes to actions that actually can be taken by the system deployed;
- **Faster deployment:** by providing the capability of learning new tasks;
- **Better situational awareness:** by combining data from all available (multimodal) sensors into a common operational picture that includes potential actions and their expected outcomes;
- **More robust operation:** by deploying swarms of drones for which the task decomposition is generated by combining different foundation models (e.g. language, vision, 3D environment mapping and properties of the robots);
- **Changing the environment**: by understanding how objects that have not previously been seen can be manipulated. For this, the affordances of these objects must be determined.

Construction

The construction sector plays an important role in the EU's economic growth. It provides 18 million direct jobs and contributes to about 9% of GDP. Nearly 95% of firms in the construction sector are micro-enterprises or SMEs, making it a primary creator of new jobs. It is also pivotal to the EU's strategic goals related to climate, energy and other social challenges. Considering that construction is a labour- and carbon-intensive sector, it is critical to support the sector to become more competitive, resource-efficient and sustainable.

Construction sites are by nature highly complex and dynamic environments, which hinder robots from following preplanned paths and executing pre-programmed tasks. GenAI can enable robots to understand their environment, generate alternative paths and invent new strategies to execute their tasks. Most of the relevant research and innovation has focused on utilising industrial robots and drones, which have inherent limitations when it comes to performing in construction settings.

However, many construction machines have the same mechanical design as robots, but are tailored designed to perform construction tasks. Recent efforts aim to make these machines more intelligent by integrating modern sensors and embedding computational capacity. To comply with carbon neutrality ambitions, many construction machinery manufacturers are investing in transforming these machines so they can be powered by batteries instead of fossil fuels.

The machines can constantly evaluate the environment based on past experiences, perform tasks autonomously, and work alongside humans, ensuring safety. The integration of these machines with information systems such as BIM (Building Information Management) will allow them to extract information on tasks that enables them to perform autonomously.

Transport

Rapid technological progress has spurred growth and innovation in the field of intelligent transportation systems (ITS), particularly with the introduction of connected, automated, shared and electric and/or renewable energy mobility technologies. This evolution in ITS technologies will fundamentally reshape our logistics and mobility systems, with multimodality, safety (including cybersecurity) and energy sobriety at their core.

The rapid development of highly automated vehicles has sparked interest in ensuring their safety, cybersecurity and reliability before deployment. With the complexity of these systems, large scale simulation models and robust testing methodologies are imperative to effectively identify and mitigate potential faults. The deployment of automated/autonomous vehicles at scale is an intricate process due to complicated transportation infrastructure and software traffic management systems. Innovative solutions are required to optimise route guidance systems, develop safe adaptive motion planning, and ensure both predictive and real-time control. The objective is the optimisation and efficiency (traffic, energy and environmental impact) of mobility and transportation systems.

Seaborne drones or ‘uncrewed surface vessels’ (USVs) are starting to be deployed in the renewable energy industry, where a key use case is the deployment of autonomous drones to map the seabed and monitor the presence of marine species, including birds and mammals. This helps overcome a key bottleneck in the permitting process for offshore wind farms, which typically requires months or years of offshore surveys. The deployment of autonomous seaborne drones is expected to help Europe deliver on its ambitious build-out targets for offshore wind.

Underwater robotics is currently mainly a focus of defence (e.g. for submarines, underwater surveillance, mines countermeasures, obstacle detections) and for deep sea exploration (e.g. for marine biodiversity, energy reserves, archaeology and geology). Nevertheless, underwater drones are playing an increasingly important role in ‘hardening’ critical infrastructure in Europe, including offshore energy infrastructure and submarine energy and data cables. The number of cables is rising with the build-out of offshore renewables, and such infrastructure is increasingly exposed to hybrid threats in light of Europe’s security situation on the eastern flank. Unmanned drones play an important role as they can be deployed in hard-to-reach areas to record and quickly respond to any unexpected events or instances of unauthorised access to sensitive sites by third parties.

Other GenAI and Robotics Markets

In addition to the use cases above, there is also high potential for GenAI and Robotics in following strategic markets: **hospitality and retail, biotechnologies, medical, chemicals and materials and aerospace**.

IV. GenAI and Robotics 4EU – a Breakthrough Europe Cannot Miss

Redefining the Limits of the Possible

The convergence of GenAI and Robotics promises to unleash a force that could redefine the limits of the possible by combining physical action and perception, cognitive prowess and adaptability. It offers potential solutions to some of Europe's most pressing societal and economic challenges, such as sovereignty, environmental conservation or digital transformation. The ability of GenAI to generalise across multiple tasks and domains will empower robots to deal with tasks they have never been trained for, which will open the door for more flexible and versatile robots.

GenAI leads to the potential emergence of new complex robotics systems and new markets for robots: modular robotics, evolutionary robotics, service robotics, social robotics, humanoid robotics, soft robotics and general purpose robotics. Thanks to GenAI, we can expect these innovations to happen at a faster pace, moving robots closer to deployment alongside us in our everyday lives, and:

- Making robots more flexible and more suitable for high-mix low-volume production;
- Designing robots to be more flexible and dynamic, so that they respond to specific need;
- Making robots easier to use and thus more accessible. This is especially important to the SME segment, where businesses currently struggle to use complex robots. Improved accessibility will not only benefit these businesses but also help bring more production back to Europe;
- Supporting targeted applications in which robots interact and navigate securely, efficiently and with accountability. Examples include the use of autonomous robots in open world applications such as open fields (terrestrial, aerial, underwater, space), public & social environments and households.

While Addressing Critical Challenges in the European Way

Ethics

The current FMs are trained on data originating from the US and China. This means that they are based on a non-European "model of the world" and inevitably reflect the culture and underlying values of the dominant sources of data and corpora on which they are trained . This raises the risk that output will be biassed towards this culture's conventions, values and views.

Moreover, languages that are underrepresented in the corpora will mostly be translated into the dominant language and then back to the initial language for the output. This might result in a reduction of the language's richness. There is a need for more research to better understand these phenomena and to develop European multilingual and multicultural LLMs from quality corpora.

Frugality

The energy cost of learning and inference with today's GenAI models is huge and represents a critical challenge. AI models that would drive robots in the production process have to meet specific requirements, including guaranteeing quality and explainability. Since they are trained on information that relates to the physical world, they would need to be fed several orders of magnitude more data than the current "virtual" LLMs and FMs, though without the current unsustainable levels of energy consumed by LLMs and FMs. To avoid this exponential growth in data and computational requirements a different approach to "Frugal AI" is required.

One such opportunity may be "Neuro-Symbolic AI "models that are open and modular in order to be able to re-use and reconfigure them without having to be rebuilt in full each time. These challenges represent an immense opportunity for Europe to build its own innovative route and capture a large share of the market for industrial automation.

Physical aspect

The design, integration, deployment and execution of tasks by robotic systems also raise critical questions. They rely on precise knowledge of the environment and interactions among system components and their environment. They must be addressed simultaneously in order to optimise the kinematics and dynamic characteristics of mechanical systems, the distribution of actuators and sensors, the required performance and the integration of means of perception, communication, human-system interaction, control laws, navigation and planning – especially in multi-robot systems.

V. There Is an Urgency for Europe to Move Forward

GenAI and Robotics can help Europe to address at least ten out of the seventeen Sustainable Development Goals that the European Union has committed to. It is urgent to take concrete next steps to fully leverage its potential and benefits.

Our Strategic Recommendations

It is impossible to foresee the future of GenAI and Robotics, or the exact way it will impact our economic, social and environmental paradigms. Nevertheless, we all agree that Europe needs to get on board now and seize the opportunities enabled by combining these general purpose technologies. Europe should avoid entering the race on the same terms as the USA and China, whose efforts are characterised by mass investment, big data and immense compute power. Instead, it should clearly define its own unique objectives through the convergence of GenAI and Robotics, charting its own paths to achieve them and take into account European strengths, weaknesses and our cultural and societal values:

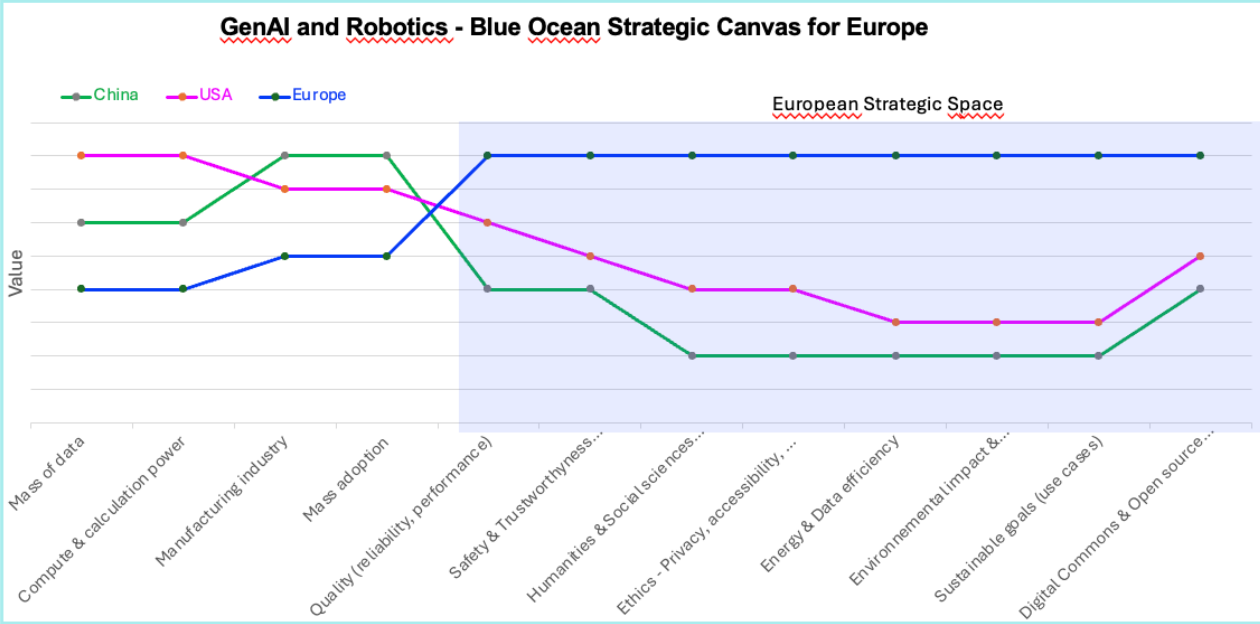
- **Economic**: growth, productivity, prosperity. Benefitting from the opportunities created by the current disruption to consolidate markets with disruptive innovation, or pioneer leadership in emerging new markets.**Social**: Preservation of European culture and values;
- **Environmental**: UN Sustainable Development Goals, including on climate change,regeneration of ecosystems, and the protection and rational use of natural resources;

1. A Blue Ocean Strategy for Europe

The Blue Ocean Strategy is a business framework which asserts that rather than competing in existing and saturated markets, the “Red Oceans”, companies achieve superior market positions by creating new uncontested market spaces, the “Blue Oceans”. By embracing this strategy, Europe can unlock potential and redefine its competitive landscape.

Europe’s Blue Ocean Strategy is to focus on values and sustainability, on social, economic and environmental levels. Refining such approaches and working on their transfer into actual business applications would enable European companies to deploy in currently inaccessible markets, opening new possibilities and a potential for tremendous economic returns. In the EU context, such an approach encompasses:

- **Safety & Trustworthiness:** Current End-to-end neural networks for robot control provide a way to reach previously unimaginable performance and versatility, but their safety is not guaranteed. Europe could pioneer new designs & processes including:
  - Safety by design, including testing in various generated situations;
  - High level of explainability, guarantees and/or certifications;
  - Specific learning methods, safe by design and physically informed;
  - New approaches to keep the system within its operational bounds;
- **Ethics, social and human criteria:**
  - Ethics and trustworthiness in correlation with human-robot interaction: equity, safety, privacy, welfare, democracy, inclusiveness (affordability and accessibility);
  - Strong involvement of social sciences and humanities experts;
  - Raising awareness to real social needs and impacts on societies;
- **Sustainability & Resilience:**
  - Enforce the "do not significantly harm" principle;
  - Encourage a strong commitment of experts in climate and environment sciences, alongside engineering experts, to reach the objectives relative to EU's Green Deal and the IPCC's 2021 recommendations for reducing the use of resources by 40% by 2030;
  - Invest in developing alternative architectures and mathematical models for Europe to be leading in the production of frugal and energy and data-efficient AI and GenAI models and advanced tensorial AI techniques;
  - Invest in transversal technologies that are reusable in different market verticals;
  - Support the eco-conception of modular, adaptable, upgradable, recyclable robotics systems and solutions to improve the life cycle and circularity of mechatronics equipment, their components and systems.
- **European Sustainable Goals**: Focus funding for GenAI and Robotics in-line with the UN's Sustainable Development Goals, to tackle major scientific and ecological challenges.
- **Invest in Europe's unique expertise**: Europe's expertise in GenAI and Robotics can be leveraged to create a unique selling position in areas such as:
  - Modular mechatronic hardware components and system configuration;
  - Embedded sensor systems with low consumption on board computers;
  - Real-time and low latency AI solutions on the edge, which combine both AI accelerators at the edge for particular workloads (e.g., perception, planning) and focus on low-latency neural networks;
  - HPC and low energy consumption computer architectures for training and inference, including the development of hardware-efficient generative AI models;
  - Translation of large foundational models on the edge for both privacy and performance reasons;
  - Full stack simulator for training and validation of complex AI models and robotic applications.



2. Educate, Train and Retain Talents

For Europe to become competitive in the rapidly evolving field of GenAI and Robotics, it is crucial to scale up GenAI education for the community. This involves developing a GenAI and Robotics literacy programme for the general public, which would increase awareness as well as fostering interest and curiosity in these advanced technologies. Furthermore, it is essential to train more highly-specialised experts in GenAI and Robotics. This can be achieved by developing high-quality, interactive courses, encompassing the key elements of the European Blue Ocean Strategy, and making these courses available across Europe. These specialised courses would provide people with the necessary skills and knowledge to contribute effectively to this field. Lastly, to hasten innovation within operational solutions, the upskilling of robotics integrators should be an urgent priority, as they will be the keystone for the adoption of GenAI and Robotics innovations.

These training programmes have the potential to raise the profile of existing European tools and solutions, as well as the constraints and limitations that they must overcome. Investing in communication with European stakeholders and promoting their ongoing developments will facilitate the adoption of their solutions. European corporations should reduce their investments in US GenAI robotics tools where European alternatives exist. Structures such as e-DIH (digital innovation hubs), clusters, and technology transfer platforms can be mobilised to organise and scale up communication within European communities.

Brain drain from GAFAM & other large corporations weakens Europe’s AI ecosystem. This can be addressed by building moonshot projects which attract and retain talent, while also committing to ambitious long-term projects, providing unique access to advanced “rare” equipment, and facilitating collaboration between private talent and public researchers.

3. Build up a Resilient and High-Performance Infrastructure for Computation, Data, Connectivity and Provide Affordable Access to It

It is important to ensure that the European infrastructure ecosystem is capable of using all necessary technologies that satisfy European standards – be they technologies developed in Europe or elsewhere - and continues to do so over the entire value chain.

This can be achieved by establishing **resilient infrastructure for computation and data**, which is capable of addressing future needs, capitalising on existing and future European instruments, such as EU Supercomputing Centers (two EuroHPC supercomputers ranked in the top 5 of the TOP 500 list), AI Factories (the first three AIFs to start operating at the beginning of 2025), European Common Data Spaces, SIMPL, IPCEI on next-generation cloud infrastructure and services, and the AIoD platform. One example is the yet-to-be-developed (Gen)AI and FM components of (large) 3D models, which will be necessary for the models' interaction with the environment and will require orders of magnitude more computational power and data storage than the current foundation models based on text, speech and video.

Access to Datasets, Compute Power, GPU/TPU/NPU

In addition to the connection with software, there must also be connections with European microprocessors and hardware development in order to enable edge AI and use of HPC. The following features must be included:

- Access to compute power: manage national and European level HPC centres and provide access to industrial players, SMEs, start-ups, researchers, which will give them a competitive advantage;
- Embedded GPU/TPU/NPU capabilities: as these are mostly built and mastered by big companies such as NVIDIA, the European Commission could offer short-term assistance to SMEs and start-ups seeking to build partnerships with major companies, helping them negotiate favourable terms, including price reductions, and enhanced technical support. In the long run, Europe will develop its own solutions to ensure supply and sovereignty.
- Datasets: Foundation and generative models are not built, but trained. This process requires a significant amount of data from many different robots, across various tasks. Obtaining this data marks the first step on the road towards large action models. Some research use simulators and synthetic data generated by GenAI to expand existing datasets[10]. We can make data more easily available, while also ensuring that it meets privacy requirements, by implementing appropriate regulation and technological safeguards that ensure it is safe for organisations to share data on the cloud. That may necessitate a EU cloud-controlled data storage, relevant not only for the use of robots in the real world but also for the research & development of GenAI.

10 Some initiatives are already underway. A project led by DeepMind, called RT-X, addressed the data shortage by creating a common format for contributions; many open datasets in this format are now provided by academic institutions and industry organisations, such as Microsoft Research https://robotics-transformer-x.github.io/

Experimental Platform: Sandbox and Test Beds

The development of a European "trying and testing" facility for robots integrating GenAI will enable them to demonstrate their capacity and safety in simulation environments. This process would include step-by-step demonstration of use cases with increasing complexity and risk. The focus should be on demonstrating relevance to society and industry and proving safety. One example of a potential initial use case is an inspection mission with robots that are proven to be safe.

Full Stack Simulator for Training and Validation

To effectively train and validate AI models, a comprehensive full-stack simulator is essential. This simulator should possess the following key features:

- Physical simulation tailored for robotics to bridge the gap between simulated and real-world environments;
- Photorealistic rendering capabilities to accurately simulate perception and enhance realism;
- Scalability to facilitate parallel training and accommodate growing datasets and computational demands. Using a physical and photorealistic simulator enables the generation of synthetic training data, crucial for robust model development.

4. Adopt a Fully Integrated Approach Between HW and SW Through the Entire Value Chain

The value chain for GenAI and Robotics is complex, encompassing both hardware and software. Each segment and sub-segment of this chain represents a market on its own, yet is inextricably linked to the others, creating a web of interdependent ecosystems. Therefore, we must support the entirety of the European GenAI and Robotic ecosystem. Efforts to develop joint infrastructure can also provide important strategic assets.

In the domain of GenAI and Robotics, we can expect an explosion of computational complexity to both train and scale such models. These models are already increasing by a factor of 100 every two years, and this trend is not slowing down. This greatly supersedes Moore's law (factor of two every two years). As a result, current foundation models can only be built and maintained with huge investments in computational infrastructure.

We have witnessed the AI software and hardware world evolving quite independently over the last decade. However, in order to tackle this increasing complexity and make AI sustainable, these two domains need to be more strongly integrated. Specific AI-robotics accelerators need to be developed to serve the complex workloads of future GenAI and Robotics applications such as control, perception, reasoning and planning. Similarly, algorithms need to be adapted to allow a more efficient run-time performance on particular accelerators.

The GenAI value chain[11] relies on (in the order of importance):

1. High-performance and low-energy consumption computer hardware for training and inference;
2. Workflow from foundation model to generative AI application (with environments for quality and performance control, including explainability, for evaluation/certification);
3. Availability of high-quality data, specially prepared for AI applications, including synthetic data generation environments and data analysis tools.

11 bit.ly/3Kh7Txzchi

The robotics value chain relies on:

1. Digital environments for design and adaptive control architecture development;
2. Sensors and sensor fusion in the edge, which are crucial for a safe interaction of robots with humans and the environment and for object manipulation. Touch and force sensors are very important in this respect;
3. Embedded sensor systems with low energy consumption, as well as actuators for interactions;
4. Modular mechatronic hardware components and system configurator.

The GenAI and Robotics value chain relies on:

1. Design of novel chip technology (transistors, memory concepts), improvements in the domain of new system architectures, improvements in algorithms, making them more hardware specific.
2. Development/verification environments for secured real-time applications.

GenAI and Robotics : Stakeholders and Intricated Value Chains

Major research scientific disciplines to invest in : Mathematics - Physics - HSS - Environment sciences

Infrastructures	Networks	Software	Microprocessors	Data	Mechatronics Components	Education & Training
Data centers Compute power Cloud	5G Edge	Foundation models Machine Learning Simulations / Digital twins Navigation & Planning Command & Control Data analysis / data fusion Edge computing Cybersecurity	Chips conception & design Chips manufacturing Chips integration	Datasets Synthetis data	Gears & motors Sensors Actuators	Research Universities Open platforms

Assembly : Intermediate components suppliers and service providers
Robot manufacturers
Distributors and service providers (applications)
INTEGRATORS
Maintenance - Upcycling - Life cycle management – Recycling

End users - Markets

Towards high-performance mechatronics and robotics hardware

To foster GenAI and Robotics ecosystems, we must:

- Establish a multidisciplinary network of premier academic research centres, using the existing Digital Innovation Hubs and extending their missions to the convergence of AI and Robotics;
- Coordinate European laboratories and industries to organise, create, and specify large datasets, which combine movement, language and vision, then collectively train models that are too expensive on a laboratory scale. This could be done within the framework of the robotics & AI excellence network EuROBIN, which includes a "dataset" dimension (the EUROCORE data portal). This is the kind of project that must be done on a large scale and would have a major impact if successful. A short-term alternative is to rely on the colossal efforts made on LLMs and, to a lesser extent, on Visual Language Models (VLMs) to connect them as "common-sense engines" in robotics;
- Create a call for projects requiring the cooperation of data, AI and robotics companies.

Co-optimisation to achieve safety, trustworthiness, resource-efficiency and high-performance

Safety and trustworthiness can only be achieved if all building blocks are designed and integrated with these goals in mind. Resource-efficiency such as energy-efficiency, while delivering high performance, can only be achieved if the hardware and software are co-optimised. It has already been demonstrated that co-optimisation of AI models together with the compute infrastructure results in vast gains in energy-efficiency. This approach should be further researched and scaled up.

Safety and trustworthiness should also be viewed from a legal perspective: through allocation of responsibility and an official qualification body. Currently, the integrators bear the responsibility which impedes their willingness to take risks inherent to innovation. The European Commission should dedicate programmes to support pioneering integrators.

5. Advancement in mechatronics

Robots are required to interact with their surroundings to execute tasks. A robot driven by GenAI will be able to make decisions on how to navigate, manipulate and operate in unplanned situations and unstructured environments. It is therefore essential that a robot is not only cognitively able to perform the tasks but also possesses the physical capability to interact with a variety of tasks. This will require continuous support for advancements in mechatronics.

6. Explore Novel AI approaches

While Europe must leverage GenAI to its fullest potential, significant efforts should be made to explore novel AI approaches, particularly those offering improvements in explainability, data and energy efficiency. These emerging AI technologies hold immense promise for bolstering technological sovereignty and European leadership within the field.

7. Develop Open Source for Community Building, Digital Commons and Sovereignty

Europe urgently needs to develop state-of-the-art technologies and to learn how to continuously and rapidly bring new AI and Robotics technologies into commercial, public, and industrial use.

This means promoting the production of digital commons for AI embodiment and large action models, including datasets, challenges, models and software development platforms with genAI.

This entails:

- Specific robotic challenges on which the community can focus to make module sharing and dataset sharing easier (as in euROBIN “competitions”);
- The production of robotics datasets on many robots and tasks, to train “generalist” robot policy that can be adapted efficiently to new robots, tasks and environments;
- Supporting the creation of European GenAI commons, i.e. datasets for training as well as for specific use cases and markets;
- Supporting the creation of an asset library containing virtual robot twins, improving user experience, mutualising efforts to collect and maintain, ensuring data quality and cyber-security.

Europe's AI and innovation communities need one or more **European open-source large action model,** which would be frugal, zero-shot, and multiplatform**.** These models can be developed using the recipe of the BigScience project, which has already produced Bloom, the first open-source LLM.

As these models are not very useful without a platform, there is also a need for a **solid open platform**. Europe should capitalise on its existing efforts to build open-source robotic-oriented platforms such as dora-rs[12] or Pollen vision[13], developing simple and unified interfaces to zero-shot computer vision models curated for robotics use cases, as well as European open source success stories such as Linux or Hugging face. These are the models that can lead to highly robust software or platforms.[14]

The governance of open platform(s) should be carefully structured to ensure European sovereignty. Putting emphasis on the interoperability of GenAI and Robotics solutions developed in Europe and creating new European licensing models can provide a path to sovereignty. To run, maintain and develop these business models, Europe will need an independent organisation for AI and Robotics. If the **AI Factories** project comes to fruition, it might be appropriate for one of these spaces, which will be dedicated to helping developers train large generative AI models, to take on this responsibility.

Consolidating all the ecosystem's needs in a single platform poses a major challenge. It will require exploring a set of platforms that would each fit specific needs. The adoption of these platforms will require open standards (OS) that allow proprietary embedding and connection. OS are particularly important in ensuring interoperability in a diverse and complex field like AI and Robotics, where various components need to interact and work together.

The platform(s) should include the following components: data lakes that include context and annotations when available, visualisation, simulation, SW components and tools (API) to design and operate robots, and computation clusters. It should be able to build private sandboxes and have enough traction to provide private companies with commercial support. Special attention should be given to ensuring the long-term sustainability of the open-source model.

GenAI and Robotics experimentation and test bed centres

Innovation follows a cycle of several iterations, in which tests and experimentations enable the maturation of robotic systems from initial readiness for operational deployment to continuous improvements. Therefore, to advance in GenAI and Robotics, it is important that stakeholders across EU Member States have access to experimentation and test bed facilities, and that those test beds are set up by EU Member States.

For these physical platforms to be economically sustainable and beneficial to the value chain, the centres must be equipped with robots from EU manufacturers and employ skilled engineers to support the stakeholders. Such centres will benefit industry, end users and research centres, helping to foster collaboration, drive innovation and accelerate technology transfer by proposing transfer instruments. EU industry would get tailored solutions for its hardware and EU researchers would gain access to API, low-level software of machines, and fast servicing of hardware, allowing

12 https://dora.carsmos.ai/
13 https://github.com/pollen-robotics/pollen-vision
14 The Open Source Robotics Alliance (OSRA, the Alliance) is a new initiative of the OSRF to organise and strengthen project governance and community involvement, launched in March 2024. Intrinsic, NVIDIA and Qualcomm are platinum members. The alliance's governance is largely taken over by US stakeholders. There is no doubt that the convergence of GenAI and Robotics will be an essential part of such an alliance.

them to conduct cutting-edge research more efficiently. Results from this research will be more easily integrated into European products. Furthermore, such initiatives will foster a robust ecosystem and technological leadership within the European GenAI and Robotics field.

These experimentation and test bed platforms can be created by extending the existing network of technical platforms across Europe, notably the Edge AI Testing and Experimentation Facility and the European Digital Innovation Hub. The Edge AI TEF is a "joint distributed platform", and its development is led by European centres of excellence in microelectronics technologies and key industrial players in the microelectronics ecosystem. The TEFs will provide SMEs and start-ups "fast and simple access to world-class testing facilities and rich networks of stakeholders and potential customers." This access will come through a network of European Digital Innovation Hubs – one-stop shops providing access to technical expertise and experimentation. Specifically, the Commission is seeking to ensure European industry will have access to "trusted, high performance, low-power edge components and technologies to support the massive data-processing requirements of AI and the digital transformation".

Phi-Lab could also be an inspiration. These are innovation hubs being built by the European Space Agency (ESA) in member states, to serve as a bridge between academia, industry and the ESA, promoting cutting-edge research and practical solutions for space and Earth science challenges. Coordination between the sandboxes for the AI Act and the test beds should be assured.

Related Recommendations

1. Articulation Between Strategies

In the context of a rapid technological evolution and initiatives launched by stakeholders and member states, collaboration is key to enhance our competitiveness. Better coordination, information sharing and dissemination are crucial. Creating a **European GenAI and Robotics Multidisciplinary Institute** could support such collaboration. To accompany the vital European transformation towards an AI & Robotics powered society, this Institute could be a part of a broader Moonshot project.

Europe has to define its own new societal model. Its technology sovereignty, as well as its economic, social and geopolitical development and leadership, are at stake. As such, we recommend that the Institute's role and actions in the short term would be the following:

- Launch technology and track the GenAI and Robotics market;
- Guide GenAI and Robotics research and innovation actions towards sustainable goals and social outcomes, in tight cooperation with HSS and earth and environmental sciences, s with a focus on relevant use cases as a driving force for technological development;
- Establish and promote the adoption of ethical guidelines for the use of GenAI in robotics to ensure responsible development and deployment;
- Coordinate the various European GenAI and Robotics initiatives to ensure knowledge-sharing and foster cooperation among all EU players;
- Create a framework to study the appropriation processes and their social impact, paying attention to the Jevons paradox which highlights a counterintuitive situation where improvements in the efficiency of resource use can lead to an overall increase in the consumption of that resource, rather than a decrease;
- Create and facilitate collaboration within a web of transdisciplinary interdependent networks

of players covering the complex value chain of GenAI and Robotics, including both hardware and software actors as well as HSS and environmental sciences experts and stakeholders;

- Elaborate and publish sustainable foresight scenarios of desirable futures and models, and propose research and innovation pathways for GenAI and Robotics to contribute to sustainability goals;
- Evaluate and report technological milestones and foster technology transfer to European industries;
- Establish and track measurable goals for GenAI and Robotics e.g. in terms of reduction of greenhouse gas emissions.

2. Private Capital Funds for Scale-up in Europe

European AI and Robotics companies benefit from a high level of collaboration with world-class research and innovation centres, including significant funding through programmes like Horizon Europe. While public investment may not be comparable to the US or China's programmes, this is not the primary obstacle. The real issue is the lack of private industrial investment in maturation and deployment phases, particularly in robotics hardware companies. Insufficient funding can constrain the scale and scope of our AI and Robotics initiatives. Encouraging European investors to fund cash-intensive, high-risk, high-reward projects like robotics hardware production would greatly benefit European robotics and its citizens in the long-term.

3. Policy and Standards

European policies need to be aligned with each other in the areas of AI, Robotics and related fields, including 5G, supercomputers and electronics. The integration of GenAI in Robotics must be established within a reliable regulatory framework that strengthens and does not hinder GenAI and Robotics innovation. Standards should intertwine methodological and technological developments with ethical and environmental priorities, reflecting Europe's tradition of strong values.

Standards must be adapted to be actionable and suitable for the digital era. This objective is ingrained in the concept of SMART standards[15] which can be viewed as a cornerstone for the integration of GenAI and Robotics. Engaging with standardisation organisations on SMART to assess their current status and potential contributions represents a next step forward. The principal effort must now go to innovation and not regulation.

4. Support AI Adoption, Notably for SMEs

Sensibilisation of audiences outside the fields of AI and Robotics plays an important role in the adoption of GenAI and Robotics solutions. Demystifying these technologies is important so that policymakers and public understand the capacities, limits and perspectives. By changing the business models of many companies and creating entirely new ones, AI could boost profitability rates by 38% worldwide, leading to an economic boost of €12 trillion across a variety of industries by 2035. Considering that 40% of Europe's self-proclaimed AI start-ups do not use AI technology in a way that is essential to their business[16], support is needed to help SMEs better evaluate the risks and benefits when choosing between engineering a solution to a problem or investing in ML to solve that problem.

It is also imperative to bridge the gap between end-users and solution integrators. There is a significant divide between industrial end-users, who are eagerly awaiting mature "AI solutions"

15 https://experts.cen.eu/key-initiatives/smart-standards/ ISO & IEC https://www.iso.org/smart
16 Innovation Paths for Machine Learning in Robotics [Industry Activities] | IEEE Journals & Magazine

but feel unequipped to navigate them, and the vast community of researchers, technologists and equipment manufacturers who are often disconnected from the end-users' realities. The disconnect hinders the development of relevant and mature AI solutions for industry. There need to be more relevant use cases provided to the community and greater awareness raised among end-users. This could be the role of integrators who would serve as mediators, channelling innovations and new developments from the community to the industrial end-user.

VI. Technology Roadmap for Europe to Take Leadership in Explainable, Safe & Trustworthy GenAI and Robotics

The GenAI and Robotics Technology Roadmap targets several strategic levels:

- Reinforcing the development and dissemination of learning and adaptation software platforms for robotic systems, integrating foundation models (FMs) to enable context-aware robotic systems by enhancing the robot's ability to perceive and interact with the environment;
- The emergence of an offer for GenAI-based software for accelerating robot design, control system engineering and integration into digital environments and real-life operations;
- Exploring new frontiers in end-to-end intelligent full-stack system design, with increased efficiency and reduced environmental impact, thus stimulating the required collaboration between hardware and software to tackle the challenges of GenAI support Robotics;
- Developing GenAI-based Robotics solutions that are human-centric, safe, trustworthy and aligned with European values.

The roadmap is articulated into short-, medium- and long-term objectives. While this categorisation is based on the expected achievements of the objectives within the timescale, all the below mentioned topics should be addressed immediately.

1. Short Term Objective: Accelerating the Implementation of GenAI into Robotic Systems and Opening up to More Complex Applications, in up to 2-3 years

To advance the development of GenAI and Robotics, it is essential to foster adoption of current state-of-the-art FM and GenAI techniques in robotics systems, especially towards integrators and large corporations in strategic target markets, creating accessibility to the current AI, while at the same time investing in potential pathways for future advancements, aligned with European ethics and sustainable values. Special emphasis should be put on the interoperability of GenAI and Robotics solutions developed in Europe. We must consider the entire value chain from a European perspective to guarantee European competitiveness.

A comprehensive suite of software solutions

The integrators should adopt advancements through a structured offering of software toolchains.

These toolchains should use large foundation models (LFMs) to address functions that currently limit the deployment of robotics, such as multimodal perception, task programming and planning/ decision-making. These functions require highly specific and advanced skills. LFMs simplify the implementation of these functions, provided that a comprehensive suite of software solutions emerges.

Major issues to be addressed in the first phase are the simplification of the GenAI-empowered software development process, the data and energy costs for the developments and the lack of adaptability of learning processes. One of the principal characteristics of robotic systems is their intrinsic adaptability, and there is a need to design robotics systems that can cover a broad spectrum of applications.

The expected outcome is the wider adoption by integrators of advanced technological bricks, larger set of functions, greater adaptability of robotics systems and an accelerated deployment of advanced robotics systems, including within SMEs.

TECHNOLOGY

Technology readiness levels of the sectors below are expected to increase from the current range of 3-4 to 7-8 within the next 2 to 3 years.

1. Data collection & Unified European Framework

The prerequisite for developing GenAI-powered Robotic systems is data. We need to establish a **unified European framework to collect, store, share and protect data.** This framework must include **scientific methodologies for safety and transparency** when using datasets, whether real-world or synthetic, for efficient training of FMs. European Common Data Spaces have been developed over the past few years and can constitute a good basis to build GenAI-specific dataspaces for robotics. EU companies should be prioritized over the US or Asia in accessing and using this data. The framework should also define ambitious, yet achievable objectives for embedded computing and communication resources to embed GenAI in robotics equipment safely and reliably. A dedicated programme to collect data should populate the framework with a broad range of examples of actions from different European institutions and organisations. The framework should support the development of real-world industrial datasets, specific to targeted markets and their use cases. The process must also ensure alignment with European values.

To foster collaboration, there must be strong incentives for European companies and institutions to share their data to develop **unified datasets** that they will be able to benefit from, and therefore enhance efficiency of their processes. The economic activity can be boosted in such key fields as automotive, an early adopter of these technologies, manufacturing, energy or infrastructure. The data should not be limited to data directly useful for the training of models themselves, but include other additional existing data that will be useful to ensure that AI-powered robots perform industrial tasks consistently. For example, in manufacturing, data could include products, tools and factory layout information from EIS, ERP, and MRP systems, such as CAD/CAM/CAE designs, PLM data, PPC data, BOM, routing sheets, work methods (e.g., MTM analyses), assembly instructions, etc. . This data can be extremely useful for robot tasks such as planning, deciding grasping strategies or automatic programming of robots.

In each instance, it will be important to launch initiatives that involve economic players, for example dataspace projects that gather a small number of key end users of AI-powered robots in a given sector, dataspace players and service providers if necessary, and AI-powered robot manufacturers that will be able to use the data and offer early privileged access to the AI-powered robot solutions to the involved end users.

To accelerate on specific high-impact use cases that are to be identified within strategic sectors, we need **application-specific dataspaces** to be developed. Sharing proprietary data by private companies represents significant challenges, for example the risk of exposing internal processes. The creation of sandboxes offers a viable solution, enabling the controlled creation and utilization of data in a secure, collaborative environment and providing early access to end users. As data sharing implies challenges related to market dynamics, including questions of pricing, the effort required for data production and value attribution, we also need a broader reflection on the European economic design space and the development of sustainable monetization models for these dataspaces.

2. Multimodal European Foundation models and Hybrid AI

We must develop hybrid European FMs and task-specific adaptation processes to fuse heterogeneous data into pipelines for multi-modal perception. This will require combining Large Language Models (LLMs), Large Vision-Language Models (VLMs), Large Action Models (LAMs), Large Audio-Language Models (ALMs), Tactile-Language Models (TLMs), Time-Sequence Models (TSMs) and Large Visual-Navigation Models (VNMs), which can then be used to improve various tasks in robotics settings through a multi-modal representation of the operating environment.

Further research and development should be undertaken to address scientific issues related to **multimodality**, the integration of physical constraints in LFMs, and the safety requirements related to robots, thus improving safety, trustworthiness and data-efficiency. These multimodal European FMs can be open-source, provided we establish a sovereign sustainable European open source framework.

Additionally, ML can and should be hybridised with symbolic AI and other techniques for trustworthy operation in uncertain environments and efficient task-planning and supervision. The development of these environments for end-to-end control should receive significant investment as it will be a step forward in simplifying end-to-end control design, but more importantly, it will be an important stepping stone to deploy increasingly more powerful AI in a controlled manner.

3. Foundation models which can function on the edge

We must explore the potential of connecting different FMs and then fine-tune, train and refine them, particularly in order to optimise their run-time (e.g. in the different European languages) so they can function on the edge, taking into account principles such as privacy and performance.

This will lay the ground for integration in low-risk solutions for more efficient human-robot interaction, e.g. user-programmable systems using natural language, as well as robot-robot interactions. One objective should be to provide a task-grounding robot programming "language", enabling the determination of useful sub-goals based on high-level instructions and learned affordance functions, allowing robots to identify actions and execute a task. Another short-term objective is to enable interactive task programming for manipulative robotics. This can be achieved through action recognition (based on visual and interaction forces data) and planning of action sequences with the help of demonstrations based on a robot's awareness of its environment.

GenAI inference on edge devices is a key topic to bring edge-based applications closer to the end-user, through techniques like quantisation, flash attention, and speculative decoding. This will need to go hand-in-hand in the short-term with the introduction of more AI-capable chips by mainstream consumer electronics vendors.

4. Machine learning techniques for real-world environments

For robotic systems operating in real-world environments, high-level planning using synthetic data could be investigated in addition to FMs to improve data efficiency and enhance contextual understanding. This data can be produced through continuous learning simulations and techniques such as imitation learning and reinforcement learning through language-driven rewards. This will require intensifying investment in synthetic data generation via GenAI for robots to handle complex and unknown real-world situations more effectively. To ensure that the generated data is relevant, a fast, automated parameterization of the specific real-world environment, e.g. manufacturing, to define the bounds of synthetic data needs to be implemented.

We need also to explore **Federated learning** techniques allowing multiple robots to train collaboratively a shared model while keeping the data locally to ensure their privacy. To enhance computation efficiency and scale training for large datasets that exceed the capacity of a single machine, **distributed learning** is also critical, as it enables parallel processing across multiple devices, ensuring faster training and effective handling of complex models.

5. Develop GenAI-driven design; optimise system design and integration

GenAI is an essential tool in the design phases of robots and robotic systems, which are by their very nature multi-physical, scalable and reconfigurable systems, integrating software components, sensors, communications, interfaces, etc. These systems often need to be integrated into systems of systems, as is the case for production resources or complex operations requiring the deployment of multi-robot systems. They have to meet a large number of constraints, including functional, manufacturing and performance requirements, as well as design features covering the entire product lifecycle (eco-conception, environmental impact, energy consumption, maintainability, etc.). Using GenAI techniques allows for the production of models that approximate the physical features needed for performance evaluation and design optimisation. Meta-models, integrating uncertainties and exploiting several levels of fidelity, can be produced using stochastic processes. Design phases can also be enriched by the use of modular or even atomistic approaches to generate models at different scales, coupled with global optimisation methods with sequential decision processes that can be formalised and solved by learning.

6. Design modular mechatronic hardware components and innovative heterogeneous multi-robot systems

The design of heterogeneous multi-robot systems, which can cover a broad spectrum of applications (land, aerial, sea), is opening major new market opportunities in which Europe can become a pioneer. The target markets are huge and strategically important. Europe has major leading corporations in the aforementioned sectors and a very dynamic entrepreneurial community in drones, which, coupled with the excellence of our research, can be driving forces for Europe's global leadership in multi-robot systems.

GenAI design approach can be used to develop modular mechatronic hardware components (gears, motors, batteries, actuators) to meet the specific needs of robotics, which must currently rely on components developed for other fields. This will significantly accelerate the innovation process especially for the complex soft robotics design.

7. New architectures for sense-plan-act paradigm

GenAI promises to endow robots with rich semantic understanding of their surroundings by leveraging LFMs trained on very large datasets. Initially, this improved semantic reasoning should support the development of robotic applications with more flexible human-robot interactions by interfacing LLMs and state-of-the-art speech recognition systems or graphical user interfaces. However, the aim of general-purpose FMs is to directly map sensors to actuators, providing open-vocabulary robot navigation, manipulation and planning.

To make the most of foundation models, Europe needs to invest in the research and development of new system architectures, blending perception, LFMs and motion as fluidly as possible, encompassing safety, data, energy efficiency and sustainability. By leveraging small and TinyML concepts with edge computing and new model architectures, we can make ML models smaller and hence more accessible and frugal in terms of data and energy resources. Devising such architectures, which involve a tight coupling of hardware and software components, should be carried out by a collaborative effort of start-ups, SMEs, large companies and academic institutions.

One particular challenge to be considered in this first phase is the dissemination of these technologies among robotic system integrators and their appropriation for productivity and performance gains in robotic system deployment. As it is essential for ensuring the safety and reliability, **cybersecurity** should be addressed alongside the development of new system architectures. It must be a key consideration in the design and deployment phases of GenAI Robotic applications in order to safeguard both the technology and its users.

ARTICULATION WITH RELATED FIELDS

- European embedded and advanced cloud computation capabilities for model training;
- Electronics;
- Cybersecurity;
- Edge computing;
- Given the ethical, legal and societal impacts of GenAI, it is essential to address issues pertaining to its deployment in robotics in a cross-disciplinary manner, teaming robotics with philosophy, law, psychology and sociology.

TARGETS

- Qualified data framework;
- Multi-modal GenAI algorithms using video and sensors as inputs;
- Hybrid symbolic - generative AI;
- Improvements to FMs, making them more hardware specific, particularly in relation to run-time performance, achieved via AI accelerators;
- GenAI for action generation, with a deep physical understanding of both perception and action;
- Design of new system architectures, integrating hardware and software components;
- Proof of concepts and prototypes of general purpose robots;
- Robots capable of performing tasks such as pick-and-place based on instructions given in natural language, in relatively structured environments.

2. Mid-Term Objective: Europe Becomes a Leader in Explainable, Safe and Trustworthy GenAI and Robotics by Accelerating Development of Critical Components and Engineering of Safe Robotic Systems, in 3-5 years

Robotic systems must be optimised for the specific tasks that they are to carry out. Moving towards a more modular robotics approach, the development of control systems can be based on AI technologies, with their implementation being rigorously managed to meet safety and security requirements for the certification of components and systems. In this context, AI based on LFMs should act as a catalyst for systems engineering.

The requirements of safety-critical systems for GenAI applications in robotics include the use of robot-relevant training data, safety guarantees, uncertainty quantification and real-time execution. Safety evaluation may rely on rigorous tests of an FM-based robotic system prior to deployment, model updates throughout its lifecycle, and continuous monitoring during operation. Meeting real-time constraints is also challenging due to the high inference time of some FMs, which could hinder their deployment and fail to sufficiently accelerate inference to the speed required for online computations.

TECHNOLOGY

Technology readiness levels of the areas below are expected to increase from the current range of 2-3 to 5-6, in 3-5 years.

1. Robot control design empowered by AI

FMs and reinforcement learning enhanced by LLMs and VLMs should be used to provide unified frameworks for end-to-end robot control that combine perception, control, decision-making, and action generation, and to support robotics in learning non-predefined tasks. To this end, ML can be used to estimate parameters, models, shapes, maps, etc. It simplifies the synthesis of control laws and is the key to controlling systems for which the construction of a model is problematic.

GenAI will only be optimally usable in a robotics environment (on the edge) if both the software and hardware functions are optimised, allowing for the compute to take place. To achieve this, hardware developments are needed to support the computational complexity of the GenAI models functioning on the edge.

2. Trustworthy and verified implementation

Within the robotics context, training data and its source, composition and governance are essential to managing AI workflow. But deploying LFMs in robotics raises specific issues about safety, since these systems can produce incorrect content due to spurious correlations (e.g. hallucinations). They may produce flawed plans of actions, which will have irreversible effects. Furthermore, the semantics in LFMs are related to the statistical correlation with the model and might not be grounded in the real world. This can have severe consequences in safety-critical applications, as well as ethical and even legal consequences in applications where robots interact with people and have impacts such as discrimination, breach of privacy or infringement of fundamental rights. Therefore, LFMs should be embedded in an architecture that includes supervision and fault tolerance capabilities.

Deploying LFMs in safety-critical applications must include constraints on real-time execution, high classification/detection accuracy, and resilience and adaptability in dynamic and unpredictable environments, to ensure the same adaptability in the robot. A LFM must also be able to perform multi-task inference in robotic systems with strict resource and real-time constraints.

We must develop methods and environments (possibly by means of hardware-in-loop simulation) for the verification of time constraints, memory access capacities and speed, energy consumption requirements, and operating safety and security. Frugal and secure embedded computation components (non-GenAI algorithms) dedicated to GenAI robotics must also be developed.

3. Develop robust GenAI-empowered sensing approaches

There is a need to further develop GenAI-empowered sensing approaches, with related sensor fusion techniques and actuators, to be combined in robotics. This will support data capturing and allow functioning in real-world environments.

4. Invest in real-time and low-latency GenAI solutions on the edge

For both privacy and performance reasons there is a need to invest in real-time and low-latency GenAI solutions on the edge, which combine both AI accelerators for particular workloads (e.g., perception, planning) and focus on low-latency neural networks. Such investments will be essential to allow private, energy efficient and performant GenAI applications closer to the end user, e.g. personalised chatbots that can learn an individual's personality. Furthermore, intelligently communicating decentralised information storage and computation in the cloud-to-microcontroller continuum should be a priority. European sovereignty could be ensured through European communication protocols for the edge. Alignment with the EU Data Act (e.g. multiparty access to edge/Iot data) and the EU Data Strategy (e.g. data spaces) should be ensured in order to level the economic playing field for large companies and SMEs through increased data access.

5. Develop innovative hardware platforms and systems

This includes GenAI-embodied humanoid robotic systems with enhanced navigation, interaction and manipulation capabilities for social, healthcare and assistive environments. These systems should be programmable by users using natural language and should seamlessly integrate into human environments.

Multi-robot systems represent another important area for development. For environments that are difficult, dangerous, hostile or inaccessible to humans, heterogeneous robots are of particular interest. Generative design and complex systems simulations will enable the development of out-of-the-box robotics platforms (soft-robotics, polymorphic robots, modular-robotics) and the deployment of swarms of heterogeneous robots with innovative task, distribution and command and control mechanisms through HRI and robot-robot interaction.

6. Develop intelligent, interoperable data spaces to open up new uses for data

As dataspaces develop and become interconnected, the amount of data generated will grow exponentially. New models will require larger amounts of multimodal high-quality data to fulfil their potential, but the resulting abundance of information will become more difficult to manage and exploit efficiently. Edge-to-cloud paradigms will open up the opportunity to reroute data from the companies or organisations where it has been generated to third parties that need it (e.g. to train models), and eventually generate data on-demand in order for AI model creators to generate new, more performant solutions faster. The use of AI-generated meta-data and GenAI or hybrid agents to drive data exchanges across dataspaces will accelerate the deployment and economic impact of the European AI ecosystem.

7. Develop GenAI robot systems that are aligned with human values

GenAI techniques have the potential to generate plans on the basis of the knowledge extracted from the large datasets. This knowledge is, by definition, not well formalised; the key strength of GenAI approaches is the ability to automatically extract it. This means it is difficult to predict what the systems will propose. They may "hallucinate" and propose unrealistic plans, but they may also propose solutions that are not compatible with their social environment. If no special care is taken, they may, for instance, propose a set of actions that can unintentionally harm humans or animals. There is therefore a need to identify means of governance for AI decision-making and develop methods that will enforce the safety of these approaches and ensure that they are aligned with human values. This can be done through various approaches, including backward alignment, which consists of analysing the propositions of the GenAI techniques and checking a posteriori their compatibility with human values. This approach has the advantage of being compatible with any GenAI technique, and it can rely on classical AI methods or hybrid approaches. The alternative is to perform forward alignment, in which the design process of the GenAI technique includes these notions at its core, to generate results that are intrinsically compatible with European values.

ARTICULATION WITH RELATED FIELDS

- Development of high performance (HPC), networked HPC (for example, by exploring the use of AI Factories) and low energy consumption computer architectures for training, finetuning and inference of GenAI models, as well as run-time optimisation, including the development of hardware efficient GenAI models;
- Embedded sensor systems with low consumption on board computers;
- Development of simulations of complex systems and advanced digital twin technologies;
- Advanced integration of cross-disciplinary approaches to address the ethical, legal, and societal impacts of GenIA in robotics, involving the collaboration between robotics, philosophy, law, psychology and sociology.

TARGETS

- First solutions for hallucination mitigation and ensuring decision safety;
- New meta-models for robots, built on multiple FMs, which are capable of planning and executing several tasks in the open world;
- Specific AI accelerators developed to serve the complex workloads of future GenAI and Robotics applications such as control, perception, reasoning and planning;
- Successfully integrated language and motion models and training of specific language/common sense/reasoning/vision models;
- Safe development solutions deployed in GenAI-based robot usage;
- Solutions for a simple situation in an open world;
- Multi-robot systems (swarms of heterogeneous robots) integrated in a production process;
- European communication protocol for the edge;
- Access provided to European stakeholders for high-quality data across sectors and borders to

support AI-enhanced robotics applications;

- Seamless and automated connection between robots/GenAI and data space ecosystems, with bi-directional flow of data.

3. Long-Term Objective: Europe Defines the New Frontiers for GenAI and Robotics, in 5-7 years

As GenAI advances at a remarkable pace, predicting the long-term trajectory of research and applications remains inherently challenging. Recognising the uncertainty in this domain, this roadmap must regularly undergo updates and reviews to incorporate new technological disruptions, from quantum to DNA data storage and organic electronics, as well as the changing social, economic and geopolitical context.

Long-term research must aim to enable the development of comprehensive environments with agnostic control/programming for design, continuous learning for adaptation needs, and reusability. It should set ambitious objectives, relying on short- and mid-term advancements, with the overarching goal of making robotics simpler and more accessible, while guaranteeing environmental, ethical and sustainability values.

Longer-term objectives may of course concern a number of research questions on LFMs themselves, as well as seeking to exploit the potential offered by future development of FMs for robotic needs. Work should be undertaken to highlight the need for adaptability and resilience of robotic systems, continuous learning throughout the life of robotic systems, as well as system design principles that seek overall optimisation of resources. This should also take into account all constraints linked to functional requirements, i.e. those of production, certification and the life cycle of robotic-based systems.

Further, we need to invest in developing alternative architectures and mathematical models for Europe to be leading in the production of frugal and energy and data-efficient AI and GenAI models and advanced tensorial AI techniques.

TECHNOLOGY

Technology readiness levels of the areas below are expected to increase from the current range of 1-2 to 4-5/6, in 5-7 years' time.

1. Towards general-purpose robots via foundation models

Building general-purpose robots that can operate seamlessly in any environment, with any object, using a diverse range of skills to complete various tasks, has been a long-standing objective in the field of AI.

The questions raised by the design, integration, deployment and execution of operations by a robotic system require precise knowledge of the environment and the interactions between components. They must be addressed simultaneously (through a fully integrated hardware and software approach) to optimise both the kinematics and dynamic characteristics of mechanical systems, the distribution of actuators and state sensors, the required performance and the integration of means of perception, communication, human-system interaction, control laws, navigation, planning, etc., for systems that may be multi-robot. Given their level of complexity, the engineering of robotic systems and their deployment requires the use of modelling, simulation, performance analysis, information processing, programming and interaction techniques, all of which already make extensive use of AI tools. However, in the lon- term, we can envisage these different phases utilising knowledge models and multi-scale synthesis methods, taking advantage of GenAI and reinforcement learning techniques for global optimisation and the optimisation of individual components while simultaneously considering all the parameters of these systems-of-systems.

2. Lifelong continual learning

Learning methods are designed to use static data. This results in significant practical limitations when they are deployed in dynamic environments and are confronted with unknown data. Continual learning, achieved by using large, pre-trained models, may be a solution. However, deploying such models in stand-alone mode is currently impossible in many frugal applications that impose heavy computational and/or memory constraints.

3. End-to-end robot design and Sim2Real

The long-term strategy in GenAI Robot design involves addressing the principles of the Advanced Multifidelity Multidisciplinary Design Analysis Optimisation (AMMDAO) methodology. This approach enables the analysis and optimisation of a complete system by explicitly considering significant interactions and synergies between disciplines, thereby formalising the design development process. Integrating this design environment with a multi-fidelity "digital twin" allows for the training of AI models and the evaluation of their performance to represent the necessary variability in the state space of operations and to produce large numbers of simulations within a limited timeframe.

This includes integrated product generation (generative design modules), production processes and engineering for the design and execution of complex robotic operations, multi-physical, scalable and reconfigurable through multi-robot systems (swarms of heterogeneous robots) working alongside humans, but also the supervision and situational awareness of more complex, deformable robots through simulation-enabled situational awareness.

4. GenAI robotic systems that are aligned with human values

The long-term strategy towards GenAI robotic systems that are better aligned with human values demands an approach where the objective to align is incorporated from the very beginning of the training process and involves interactive learning with humans in the loop. This approach is called forward alignment and complements the mid-term backward alignment objective, which consists of analysing the proposition of the GenAI techniques and checking a posteriori their compatibility with human values in general – and European values in particular. By contrast, under a forward alignment approach, the GenAI design process includes these notions at its core, ensuring that the generated results are intrinsically compatible with human values. This approach requires close collaboration with disciplines such as philosophy, law, sociology and the humanities to ensure that the human values incorporated in the training of GenAI robotic systems are well-defined, consistent with moral philosophy theories, compliant with European laws and considerate of socio-economic contexts. Additionally, the approach implies the inclusion of human users at various phases of the training process, to take into account the variety of human preferences, acceptances, reactions, misinterpretations and cognitive biases. This will train GenAI robotic systems to acquire internal world models taking into account the variety and explicitly estimated uncertainty of the effects their actions can have on human users. The last requirement is to conceive planning methods for GenAI's learned internal models, to anticipate and foreseek risks for human values, search for action plans that respect and even promote human values, and inform humans about the estimated uncertainty about these possible consequences before taking action.

ARTICULATION WITH RELATED FIELDS

- Further development of HPC and systems for large-scale simulation for training robots;
- Large-scale simulations;
- Reliable and distributed connectivity infrastructure and distributed network;
- Cloud-to microcontroller continuum.

TARGETS

- Safe, interactive and useful social general-purpose robots, including but not limited to humanoids, which execute complex tasks given by people in natural language with high-level commands in unstructured social environments. The robot is accepted by people it encounters and complies with social norms;
- Distributed aligned GenAI robotics: multiple interconnected components and machines that work together in an efficient and adaptive way at the edge as a single system. A mass of data being generated by people and machines from production floors makes us rethink where computing needs to be performed;
- Real-Time autonomy and adaptation of GenAI robotics systems;
- Fully autonomous and self-configuring integrated robotics systems for complex tasks in open and/or unstructured social environments;
- Cloud-based robot management and coordination;
- Enhanced communication and collaboration with 6G;
- Out-of-the-box robot and robotics system design. Here, we will see the results of prior investments in the generative design of robotics systems, notably with soft-robotics and polymorph robots;
- Design and development of capabilities for the deployment and interaction of robotics swarms, in various constellations and working alongside people.

Transfer of mature engineering of robotics systems and their integration in "systems-of-systems" to industry. From a set of high-level objectives and constraints, integrating the "Blue Ocean" criteria (HSS, safety, trustworthiness) dedicated generative design tools will greatly simplify and automate the mechanical and process engineering.

VI. Conclusion

The convergence of GenAI and robotics is an area with huge potential, highlighting the critical role of robotics in fully unlocking the transformative potential of GenAI.

It is imperative to support and sustain investment in European GenAI, with a focus on establishing robust data frameworks and fostering the development of safe, trustworthy, ethical and frugal European foundation models that reflect our culture and values.

At the same time, we must transcend the overwhelming hype surrounding GenAI progress and prepare for unprecedented developments in GenAI robotics through an integrated hardware and software approach. As a priority, Europe must commit to significant investment in the fields of physics and mechatronics in order to enable GenAI to have an impact in the "physical realm". Investments in innovation targeting the physical components of robotics, such as sensors and actuators, as well as in out-of-the-box robotics, are of crucial importance. To keep added value within Europe, we need to adopt financial and temporal metrics specific to hardware, acknowledging the field's longer maturation period and higher capital intensity with more stable financial returns on investment.

As GenAI empowers robotics to bridge the virtual-to-real-gap, it also raises crucial concerns about safety, energy efficiency and trustworthiness. These represent critical challenges as well as an immense opportunity for Europe. Leveraging its excellence in research and deep tech, alongside its entrepreneurial dynamism, Europe must urgently forge its own path by mastering these challenges and take leadership in aligned GenAI robotics, in order to serve as an enabler of this necessary transformation that is shaping the sustainable future of society.

ANNEX 1: Acknowledgements

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Human-Machine Interaction

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- Michael Ahn et.al., « Do as i can, not as i say: Grounding language in robotic affordances." Conference on Robotic Learning, 04 2022

Robotics empowered by AI

- Creating better reward models: as a component of the reinforcement learning systems used in robot training. https://venturebeat.com/ai/how-generative-ai-is-making-robots-smarter-more-capable-and-more-ready-for-the-mainstream/

Perspectives

- PaLM-SayCan: Towards robots that can understand us (https://everydayrobots.com/thinking/palm-saycan-googleresearch)
- Imec: how to industrialise AI How Imec hopes to industrialise artificial intelligence | Computer Weekly
- LLMs meet robotics: the next frontier - https://sereact.ai/posts/llms-meet-robotics

Generative design

- Large language models (LLMs) can guide the robot design process, on both the conceptual and technical level: EPFL CREATE Lab (Computational Robot Design & Fabrication Lab) - https://www.researchgate.net/publication/371397642_How_can_LLMs_transform_the_robotic_design_process - https://www.nature.com/articles/s42256-023-00669-7
- Generative design to improve robots and actuators conception. Generative representations for the automated design of modular physical robots, IEEE : https://openalex.org/works/w2167021024; Modular Robot Design Optimization with Generative Adversarial Networks: https://openalex.org/works/w4285102648; From Automation to Augmentation: Redefining Engineering Design and Manufacturing in the Age of NextGen-AI: https://mit-genai.pubpub.org/pub/9s6690gd/release/2?readingCollection=9070dfe7

AI in control systems for adaptation to complexity

- Controlling quadruped robots with deep reinforcement learning (https://laas.hal.science/hal-03761331v2)
- Equipment (Robots,.) recognition in point cloud thanks to GenAI and replace them in the virtual environment by equipment (robot,..) models containing simulation behavior.
- https://www.sciencedirect.com/science/article/pii/S0957415821000659: Active learning in robotics: A review of control principles.

Simulations of Physical world

- Open X-Embodiment: Robotic Learning Datasets and RT-X Models: https://robotics-transformer-x.github.io/ Led by Google and DeepMind, with involvement of European labs.
- Cyber-physical systems models: Perspective for more accurate data-driven simulation, testing and validation (Digital twins) bit.ly/4bQvOzl
- Focus on GenAI & Robotics for Life science: From GenAI studies of Life science, we can build biomimetic solutions to numerous ecological challenges: https://openalex.org/works/w2970568748

Manipulation

- Open X-Embodiment: Robotic Learning Datasets and RT-X Models https://robotics-transformer-x.github.io/
- Octo, an open-source AI model for generating broadly applicable general policies for robotic manipulation https://octo-models.github.io/
- DROID (Distributed Robot Interaction Dataset) A Large-Scale In-the-Wild Robot Manipulation Dataset: https://droid-dataset.github.io/
- Mani-GPT: A Generative Model for Interactive Robotic Manipulation https://www.sciencedirect.com/science/article/pii/S1877050923018161
- MIT has created a new GenAI tool that can more easily solve multi-step 3D manipulation problems https://www.extremetech.com/extreme/mit-develops-ai-to-make-robots-expert-packers

Robot-Robot interaction

- Generative AI for Unmanned Vehicle Swarms: Challenges, Applications and Opportunities, G. Liu https://arxiv.org/pdf/2402.18062

Value chain

- Exploring opportunities in the generative AI value chain, McKinsey Digital bit.ly/3Kh7Txz

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