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The acatech IMPULSE series

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Foreword

Artificial intelligence (AI) is already bringing about visible and tangible changes in our everyday lives. While language models like ChatGPT are currently attracting a lot of attention, the forthcoming revolution will bring machines into our private lives and workplaces that use AI to respond flexibly to unforeseen needs, even in the rather non-standard environments that we humans tend to occupy.

It is not just in the realm of Industrie 4.0 that AI-based robotics will enable completely new solutions to some of the key challenges of our time such as demographic change, climate change and affordable building. Robots will also literally lend us a hand in the service sector, improving healthcare and relieving us of physically demanding activities.

The next wave of automation that will accompany AI-based robotics should be used to harness the full potential of Industrie 4.0 in Germany through the combination of robotics and AI, thereby strengthening German manufacturing industry. However, it will be equally important to tap into this new technology's potential in the social arena, especially in order to address the challenges of demographic change and the growing shortage of skilled workers.

But Germany's success in this field is by no means guaranteed. The likelihood that China will overtake Germany in robot density this year does not augur well for the competitiveness of German industry. Consequently, a concerted effort will be required to use Germany's strength in research and its wide user base as a springboard for becoming a leading user of next-generation robotics. The German government's announcement that it intends to draw up a roadmap for AI-based robotics and automation should therefore be warmly welcomed.

This study is a slightly revised version of a paper that was discussed with members of the German government at the end of 2022.

acatech would like to thank everyone involved in this paper for their contributions.

Prof. Dr. Henning Kagermann,
Chair of the acatech Board of Trustees

Executive Summary

As well as being key to the **success of long-term transformation projects** such as Industrie 4.0, AI-based robotics will play an important part in **tackling major social challenges** such as demographic change. In an increasingly competitive global environment, it will also have a crucial strategic role in **securing value creation** and **maintaining technological sovereignty**.

- Automation and data-driven digitalisation are vital to Germany's long-term **competitiveness** as a leading industrial location. The deployment of AI-based robotics on the necessary scale will be a key enabler.
- Geopolitical tensions and supply chain disruption have highlighted the importance of **resilience**. In a high-wage country like Germany, extensive automation is key to strengthening industrial value creation. With this in mind, it will be crucial to avoid becoming dependent on a small number of robotics providers.
- As well as meeting the needs of shorter production cycles, flexible automation enabled by AI-based robots can also make a major contribution to achieving the EU's **sustainability goals**. Flexible automation also increases production flexibility, enables production asset reusability and makes an important contribution to the establishment of a **circular economy**, for example through scalable disassembly and recycling.
- Demographic change and the **shortage of skilled workers** mean that more and more sectors are confronted with the challenge of recruiting enough personnel or increasing productivity. However, the potential for additional increases in labour productivity without further consolidation that puts people under even more pressure has largely been exhausted. As well as industry and logistics providers, this problem is also increasingly affecting sectors such as construction, agriculture, energy and healthcare.

Thanks to the **scientific advances** of recent years, we are now witnessing disruptive growth in the potential applications of robotics technology. Whereas robots could previously only perform clearly defined tasks in structured environments, adaptive systems are now emerging that are capable of carrying out complex tasks in unstructured, changing environments – either independently or in close collaboration with human workers. At the same time, technologies are being developed to simplify the operation of robots and their integration with existing processes, meaning that many companies and industries can now use robotics for the first time.

Flexible automation enabled by AI-based robotics throughout the economy will thus be key to maintaining and strengthening competitiveness in years to come. Estimated at **260 billion euros** by 2030[1], the **potential** of the robotics **market** is huge, and there will also be knock-on benefits for other industrial sectors.

Technology leadership, access to AI-based robotics and successful ownership of **control points in robotics value networks** will be key enablers of **technological sovereignty** in a country like Germany, whose industrial success is built on mechanical and plant engineering.

Consequently, this IMPULSE publication focuses on **industry as the most important application domain** for AI-based robotics with a view to strengthening Germany's leading role in the field of Industrie 4.0. However, it is important not to overlook the strategic importance of the potential applications of service robotics throughout the economy – for instance in the construction, pharmaceutical and agricultural sectors and particularly in people's everyday lives, for instance in household and care settings.

Against this backdrop, this study analyses and discusses the strengths and weaknesses of German industry with regard to the following **key aspects of AI-based robotics**: competition, technology, the innovation and transfer process and the value network.

The study shows AI-based robotics to be a **deep tech innovation**. In other words, although it has disruptive potential that can provide a competitive advantage, it requires significant investment, and its implementation is associated with high commercial risks due to the long payback periods.

Many companies, even Germany's major corporations, are unable to meet these challenges on their own. Accordingly, an **ambitious innovation and economic policy initiative** involving government, science and industry will be essential if Germany is to become a global leader in AI-based robotics.

The user orientation and incentivisation strategy set out in this IMPULSE publication was developed as a targeted solution to these specific transfer barriers for AI-based robotics, especially during the final market development stages. It is thus intended as a complementary strategy that should go hand in hand with

1 | See BCG 2021.

strong public support for basic robotics research, which remains as essential as ever.

This paper proposes the establishment of a **leading user market** for robotics and AI in Germany in order to promote automation throughout the economy. Specifically, it will be necessary to create the **conditions** to facilitate the industrialisation and scaling of innovative robotics solutions, strengthen interdisciplinary elite research in the field of AI-based robotics and build up a sufficiently large talent reservoir. Public acceptance should also be promoted since it will be key to the medium- to long-term success of both the market and the technology. If these conditions are met, AI-based robotics can make an important contribution to Germany's technological sovereignty and economic stability, as well as opening up new value creation opportunities.

The experts interviewed for this study recommend the following measures:

- **User incentivisation:** The first step is to build user-oriented "robotopes", initially in the manufacturing and intralogistics sectors and also in certain service robotics sectors. Project funding with metrics for successful market implementation can provide a targeted economic incentive. Given sufficient incentives for users and consortium members, the relevant "robotopes" should give rise to a strong German robotics ecosystem and/or a competitive robotics original equipment manufacturer (OEM). In addition, market penetration throughout Germany's SME sector can be accelerated through small innovation projects that can be approved with a minimum of bureaucracy and through additional capital allowances for the acquisition of AI-based robotics systems.
- **Talent development:** The high and growing demand for qualified robotics and AI talents – from elite researchers to people who can apply the technology in the field – calls for extensive training measures in universities (Quality Pact for Robotics Teaching, development of Master's programmes in robotics at certain universities) and in vocational education. Targeted measures should also be taken to retain talents (including foreign talents) in Germany.
- **Promotion of research and transfer:** Germany's strength in mechanical engineering and mechatronics means that it can still build a unique position in the AI-based robotics sector. It is therefore vital to strengthen interdisciplinary AI-based robotics research, preferably in centres of excellence. In addition to carrying out basic research, it will also be necessary to strengthen the successful transfer of research outputs to (economic) applications through the transfer channel of start-ups, in order to ensure the rapid, more widespread adoption of innovations.
- **Regulation and standardisation:** Safety and data protection standards should be developed together with the robotics system. Homologation requirements that allow for easy adaptation to new settings and applications provide a key competitive advantage and a basis for scaling in the market.

Interviewees

Acknowledgements

In addition to an analysis of the technical literature and other studies, five background discussions were conducted, as well as exploratory interviews with 56 experts from science, industry, government and civil society.

The interviews were conducted between August and November 2022 and lasted an average of one hour. The aim was to identify ideas about how to strengthen value creation and technological sovereignty in the robotics sector in Germany. An open-ended discussion format was chosen to support the exploratory nature of the interviews and capture the "undertones" of the responses. This IMPULSE publication provides an overview of the main views expressed in the interviews. However, individual interviewees may have had different opinions on some of the questions. The text is interspersed with anonymous quotes from the interviews that illustrate some of the interviewees' key ideas.

The positions listed below were held by the respective interviewees at the time of their interviews.

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1 Industrie 4.0 as a driver of value creation, resilience and sustainability

The long-term goal of Industrie 4.0 is to **secure Germany's competitiveness and achieve the transition to a resilient, eco-social market economy**. However, there is still some way to go. The first part of Chapter 1 examines the main current challenges associated with this transition and takes a detailed look at how AI-based robotics can be used in a way that supports good/better jobs.

Industrie 4.0 enables **new business models** that are increasingly focused on customer benefits. Functioning economic ecosystems are key to making this possible. The first requirement for implementing the Plattform Industrie 4.0's *2030 Vision for Industry 4.0: Shaping Digital Ecosystems Globally*[2] is **trusted data sharing** within individual ecosystems and between the ecosystems of different industries. The second part of this chapter takes a closer look at ***Manufacturing-X***, an initiative to establish and provide robust funding for a data space to enable this data sharing in manufacturing industry.

The widespread **implementation of Industrie 4.0** is another important step. A technological upgrade of German industry and in particular its small and medium-sized enterprises is vital if Germany is to successfully overcome the short- and long-term challenges associated with competition and the pressure to transform. Against this backdrop, the third section of Chapter 1 outlines why implementation of the proposed measures to strengthen robotics in the context of the widespread implementation of Industrie 4.0 technologies can help to overcome these economic and social challenges.

An appropriate **regulatory framework** will also be key to enabling rapid implementation of the proposed measures. The interviewed experts advocated a more pragmatic approach so that data and AI can be used more effectively. The *German Artificial Intelligence (AI) Standardization Roadmap* provides a useful resource in this context.[3] The fourth section of this chapter examines the current regulatory barriers and also discusses the Data Act and the AI Act of the European Union (EU).

Chapter 2 completes the overview of AI-based robotics by discussing the **outlook** in two specific areas. Firstly, it revisits the dual-use debate in the context of autonomous systems[4], advocating a reassessment of this topic in the light of the current geopolitical situation. And secondly, it highlights the potential of small-scale robotics, especially in the fields of healthcare and biotechnology. It is important to start addressing and funding this promising next-but-one generation robotics technology without delay.

Chapter 3 **analyses the main strengths and weaknesses of AI-based robotics in Germany** with regard to the market and competition, the technology, the innovation and transfer process and the value network. Chapter 4 formulates a robotics strategy based on the results of this analysis, with the aim of helping Germany to achieve the overarching **goals of competitiveness, technological sovereignty, resilience and sustainability**. Finally, Chapter 5 sets out a series of concrete **recommendations** based on this strategy and the suggestions of the interviewees.

1.1 Securing competitiveness and enabling the transition to a resilient eco-social market economy

The proposed measures and recommendations are geared towards leveraging the full potential of Industrie 4.0 by **combining robotics and AI**:

- **Competitiveness:** As a high-wage country, Germany must commit to automation in order to maintain its global competitiveness and enable reshoring in certain critical areas. Flexible autonomous production means replacing inflexible production lines with **flexible production cells and learning, self-regulating automation systems**. Individual data can be used to make customised products in a cheap, mass production setting thanks to the flexible production enabled by intelligent networking. This also makes it possible to produce complex product variants. In the face of supply chain uncertainty, flexible production methods strengthen competitiveness, especially during times of crisis. The precision manufacturing enabled by AI-based robots allows standardised

2 | See BMWi 2019.
3 | See DIN/DKE 2022.
4 | See Fachforum Autonome Systeme im Hightech-Forum 2017.

end products to be made from different base products with different raw material properties or geometries.

- **Resilience:** AI-based robotics can significantly contribute to increasing the resilience and adaptability of production and intralogistics. This means that production does not come to a complete standstill even if some machines are down due to raw material shortages or technical issues. Production can continue thanks to an **automatically generated plan B** that re-orders individual production steps, uses different components, or temporarily switches to producing other products.
- **Sustainability:** Energy and resource efficiency and upcycling are core principles of the circular economy. Although they often involve additional process steps, these can be automated. Industrie 4.0's AI-based production methods aim to achieve **zero-defect production** and also help to **establish circular processes** that recycle and reuse limited natural resources. The increasing use of **lightweight design** principles means that robots are able to operate more energy- and resource-efficiently. Furthermore, data interoperability allows data such as **CO_2 emissions from production** to be collected and shared between different companies and countries. This helps industry to contribute to achieving the European sustainability goals while at the same time maintaining and growing local value chains.
- **Better jobs:** Robots significantly improve working conditions by relieving human workers of **dangerous or tiring repetitive tasks**. **Human-machine interaction** in conjunction with cobots also has great potential in this regard. Moreover, intelligent automation can increase labour productivity, helping to address the shortage of skilled workers caused by demographic change. This is not only relevant to industrial production – every sector can benefit from the use of service robotics-based assistance systems.

If autonomous systems are to be deployed on a widespread basis, it will be necessary to continue the debate already initiated by the Fachforum Autonome Systeme and the Plattform Lernende Systeme on the technology's societal implications. It will also be vital to **change user attitudes**. The opportunities of AI-based robotics for the world of work are outlined below.

Supporting good jobs with AI-based robotics

It is forecast that machines will work the same total number of hours as humans by as soon as 2025.[5] But the world of work is changing qualitatively as well as quantitatively. In the future, instead of humans and machines working alongside each other as they generally do today, there will be **genuine collaboration** between them. For instance, easily programmable **cobots** will relieve human workers of unpleasant or dangerous tasks.

Robots can perform **precision tasks** more accurately and consistently than humans. However, humans remain better at tasks involving **adaptability, creativity and critical thinking**. In many production processes, human workers and robots complement each other, creating **a symbiosis of human creativity and mechanical productivity**.

Accordingly, most of the experts interviewed do not expect human jobs to be lost to machines. On the contrary, in view of the shortage of skilled workers, they regard automation as a key to maintaining jobs through appropriate **collaboration** between humans and machines.[6] This view is supported by the fact that, at present, just ten percent of jobs are fully automatable.[7]

These new technologies can help small and medium-sized enterprises in particular to tackle competitive pressures and demographic change so that they can continue to provide good jobs. By **increasing productivity**, AI-based robotics helps to address the growing **shortage of skilled workers**. Just under **10 million plant, machine operator and assembler positions** are forecast to remain vacant in Europe alone between 2016 and 2030.[8] There is also great potential in other sectors such as caring, construction and agriculture.

The rollout of new, AI-based production methods and service robotics must be accompanied by **targeted training and professional development**. The need is huge – it is estimated that up to 85 million jobs worldwide could involve human-machine interaction. This would mean that around 40 percent of these workers would require **retraining or professional development** in order to meet the challenges of the future workplace.[9]

It will also be important to focus on the **creation of attractive new professions**. It is forecast that the new technologies will create 97 million **new jobs** worldwide.[10] Just under two thirds of the next generation's jobs do not even exist today.[11]

"Robots are not competing with humans. They are an answer to the shortage of skilled workers."

5 | See IFR 2018.
6 | Ibid.
7 | See IFR 2017.
8 | See IFR 2020b
9 | See IFR 2018.
10 | See WEF 2020.
11 | See IFR 2018.

1.2 Trusted data sharing within ecosystems

Agile, connected production process systems rely on **semantic interoperability** and access to **shared data**. These factors are also key to the emergence of new business models within ecosystems. ***Manufacturing-X*** is an initiative to create a new platform providing a **common data space for manufacturing industry** in order to enable efficient, sovereign data use.

The common data spaces *Catena-X* and *Manufacturing-X*

In order to ensure security of supply, transparency and competitiveness, the digital transformation's providers and users must be brought together in **common data spaces**. *Catena-X* is a flagship project that has established a data space for the automotive industry in Germany.

In order to leverage industrial production data in a similar manner, policymakers should support ***Manufacturing-X*** as a top-priority **flagship project** within the Industrie 4.0 support framework. The experts advocate the urgent implementation of a common data space for industry **that builds on *Catena-X* and solutions that are already established in the market**.[12]

The aim of *Manufacturing-X* is to establish a **data space for manufacturing industry** (including the mechanical engineering, chemical, energy production and building materials industries) and the main user industries and suppliers.

A key part of the project is to ensure **interoperability** of the individual data spaces of the different industries encompassed by *Manufacturing-X*. The structure of *Catena-X* and the solutions developed for it should be adapted so that the following challenges for **future-proof industrial production in Germany** can be addressed as rapidly as possible:

- Supply chain management to increase value network transparency and resilience
- Energy and carbon footprint management to identify opportunities for improving sustainability
- The use of renewable energy

The widespread operational implementation of these measures to transform industry will be strategically vital if Germany is to maintain the **competitive edge** that it currently enjoys **in key industries**.

> "It is vital for the main market players in different industries to actively support Manufacturing-X."

As well as political support, a **lean, goal-oriented governance structure** will be needed so that this initiative can be pursued with the necessary dynamism. At the invitation of the Federal Ministry for Economic Affairs and Climate Action (BMWK), in February 2023 industry associations and pioneering industrial enterprises formed a steering committee to coordinate the activities of the *Manufacturing-X* initiative until its implementation.

Implementation of *Manufacturing-X* should be guided by clearly defined milestones that allow progress to be measured. The interviewees stressed that the number of participating actors should not be the only measure of success – particular emphasis should also be placed on the **outputs**, i.e. the range of solutions and the number of actual users.

In April 2023, the BMWK published a **funding framework for supporting the *Manufacturing-X* industry initiative** and defined the criteria for determining its success. The first projects are scheduled to begin in December 2023.[13]

12 | See Plattform Industrie 4.0 2022a; 2022b; VDMA 2022.
13 | See BMWK 2023.

1.3 Promoting the widespread use of data-driven factory technologies

During the **first decade of Industrie 4.0**, some individual factory technology providers have already digitalised their product portfolio and developed various solutions for future factory information systems. In the past two years, there has also been an increasing focus on the **users of digital factory technologies**.

The latest generation of robots and intelligent automation processes are key to delivering Industrie 4.0's promise to help German industry add new value and become more resilient and sustainable. Figure 1 provides an overview of some of the **remaining technological challenges** in AI-based industrial robotics.

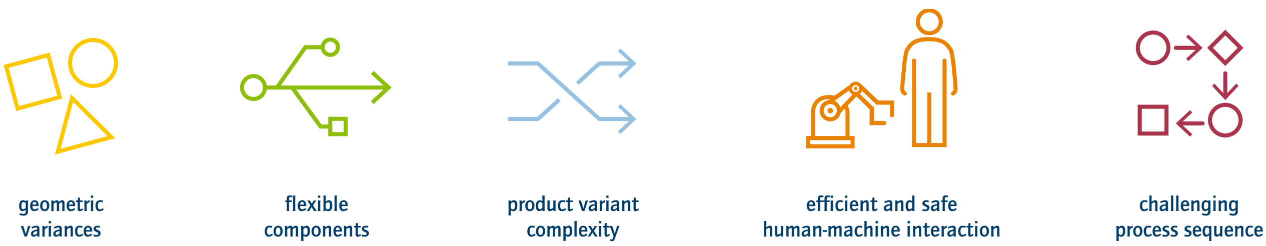


Figure 1: Technological barriers in industrial robotics (Source: authors' own illustration based on BCG 2022)

One important area for further development is the enhancement of **sensor technology** in combination with machine learning and the **haptics** of manipulators. Technological breakthroughs in these areas could significantly improve the **handling of geometric variances, flexible and elastic components and complex product variants**. **Complex** production **process sequences** also continue to pose a major challenge. Finally, another key research theme is the **intuitive and safe interaction** of robots and humans.[14]

In addition to promoting applied research and development, it will be necessary to implement widespread digitalisation of production so that Germany can become a **leading user** of AI-based robotics. However, most SMEs in Germany are still right at the beginning of this process. According to the **Industrie 4.0 Maturity Index**, which assesses companies' digital maturity level, just **4 percent of the companies evaluated have achieved maturity level 3** (visibility), which only represents the initial stage of Industrie 4.0.[15]

"Small and medium-sized enterprises are the driver of our prosperity. These companies can't afford not to digitalise and automate."

In order to maintain German industry's **competitive advantage** in Industrie 4.0 and enable the transition to a new phase, it will be necessary to implement measures across **three strategic pillars**, complemented by additional initiatives from the robotics strategy outlined in Chapter 4.

- **Lowering the entry barriers:** Sensors and machine networks form the nervous system of the digital factory. The entry barriers must be lowered even further so that smaller companies can take their first steps into the age of Industrie 4.0. This includes **free advice and information** on introducing Industrie 4.0 production processes, affordable **new turnkey solutions** and the option of retrofitting **older production assets** with the relevant technologies. **User-friendly interfaces** and the opportunity to start by trying out individual solutions without having to go through all the technological options are particularly helpful to smaller manufacturers entering the world of digital production.
- **Ease of Use:** The experts interviewed from the robotics industry report that more and more customers are asking for **affordable robots** that can be **easily installed, programmed and reprogrammed** by trained personnel. AI could make a particularly important contribution to **cost efficiency – AI could reduce** robot installation and programming costs **by 50 percent**.[16] The industry representatives who were interviewed

14 | See BCG 2022.
15 | See Schuh et al. 2020
16 | See IFR 2022a.

stressed that robots must be as easy to install and operate as an app. Simple operation and software maintenance **as a service** are particularly important for small businesses that have difficulty recruiting their own specialised personnel.

- **Common norms and standards:** Training AI-based systems requires access to large quantities of data that can only be achieved through standardised platforms. While huge volumes of data are generated every day, much of this data is unusable because it is not in a **standard format**. Consequently, the interviewees from industry called for the establishment of **data communication standards** and implementation of the *German Artificial Intelligence Standardization Roadmap*.[17] The ***Manufacturing-X*** initiative provides an excellent opportunity for German industry to create **international standards** in this area, thereby helping to strengthen Europe's future sovereignty.

1.4 Regulatory barriers in the robotics sector

In terms of Germany's ability to compete in the global market, **numerous national regulatory barriers** are holding back the rollout of Industrie 4.0 technologies and hampering the use of AI-based robotics in contexts where humans and machines interact.

The main criticism from **users** is that **over-regulation is holding back innovation** in areas such as collaborative work with cobots. The **requirements** that companies have to meet in this area should therefore be adjusted to reflect technological advances so that robots can be used in unstructured environments without safety guarding.

The stringent **regulatory requirements** mean that the use of AI-based robotics is simply not financially viable for many companies. This is exacerbated by the **lack of certified software** that would make it possible for robots to avoid approaching hazards without needing to stop, for example.

The interviewees also called for application-oriented regulation at **EU level**, with a stronger emphasis on the opportunities rather than on risk prevention. The EU's **Data Act** and **AI Act** are a particular focus of the current debate.

The EU Data Act and AI Act

The key role of European Union regulation in the digital environment

Following on from the General Data Protection Regulation (GDPR), the EU is now launching a number of **new regulatory initiatives** to govern Europe's digital future. Currently, the most important of these proposals are the **Data Act** and the **AI Act**.

In both cases, the majority of the interviewees felt that there is a danger of **over-regulation**. Some also fear that the regulatory barriers and compliance requirements will overburden small and medium-sized enterprises (SMEs) and start-ups in particular. This could give large enterprises with the relevant legal and administrative resources an unfair advantage.

The Data Act

The **Data Act** forms part of the **European Data Strategy** that was unveiled in early 2020. The European Commission's proposal for a Data Act aims to create a **regulatory framework** that optimises the **use and sharing of data** and removes barriers to data sharing. Following lengthy discussions, a draft version of the Data Act was approved by the European Parliament in March 2023, paving the way for trilogue negotiations and the potential conclusion of the legislative process by the end of 2023.

According to the Commission's own figures, **over 80 percent of industrial data is currently unused**. If the Data Act helps to make extensive use of this data, it could boost the European Union's GDP by 270 billion euros by 2028.[18]

17 | See DIN/DKE 2022.
18 | See Europäische Kommission 2022.

The sharing of industrial data is especially important for next-generation robotics – data is the key enabler of flexible production and robots that learn from each other.

Since **machine data is non-personal**, it is not directly covered by the GDPR. However, there are some **grey areas between personal and anonymous machine data**, for example the data collected from motor vehicles, including data about how they are used. Some experts fear a labyrinth of different regulations and legal grey areas resulting in protracted legal disputes and legal uncertainty.[19] In the current draft of the Data Act, the **data access and use rights** apply equally to **personal** and **non-personal data**.

The interviewees indicated that there is widespread **scepticism** about the draft Data Act within the automation industry. It is felt that the draft regulations contain provisions that would interfere excessively with corporate freedom. These include **data access and information obligations, freedom of contract restrictions** and **technical design requirements**. Many industry representatives would prefer market-driven innovations and voluntary cooperation. Some of the experts interviewed were also concerned that companies could lose **control over their data** if it is shared with third parties, potentially resulting in **trade secrets** being disclosed to non-European competitors.

On the other hand, some representatives of academia pointed out the **high transaction costs** associated with **voluntary data sharing**. In order to generate large data sets, it would be necessary to convince huge numbers of actors to share their data. From an economic perspective, it may therefore make more sense to have an **opt-out policy** for voluntary data sharing rather than an opt-in policy.

The AI Act

In April 2022, the European Commission presented a draft legal framework for the **regulation of AI systems**. The proposal aims to safeguard **users' fundamental rights and safety** in order to build trust in these technologies as they develop and become more widespread.

Most AI systems are associated with little or no risk. However, there are some exceptions that should be addressed through a European AI regulation. For example, **risks** can occur with AI-powered biometric identification systems and automated decision-making in sensitive areas such as human resource management, healthcare, law enforcement or the defence industry. Consequently, the Commission is proposing a risk-based approach with **four levels of risk**.[20]

The **mechanical engineering industry** is ambivalent about the draft AI Act. While it welcomes EU regulation of AI as an important foundation for protecting fundamental rights in Europe, it regards the Commission's plans for a **rigid, top-down risk classification** determined by the legislator as inefficient. Particular concerns were expressed about the "high-risk" classification of machine AI. Since this leaves no room for **case-specific risk assessments and measures**, many AI applications would end up being over-regulated.

Employee representatives fundamentally welcome the European Commission's draft AI Act. However, they call for all AI systems in the areas of **human resource management** and **human-machine interaction** to be classified as **high-risk** and thus subject to **third-party conformity assessment**. They also call for an **escape clause** allowing the relevant provisions of specific national regulations or collective agreements to remain in force.[21]

Some of the experts consulted felt that the proposals and ideas in the ***German Artificial Intelligence Standardization Roadmap*** offer a more practical solution than the current EU draft legislation.[22] They argue that the roadmap addresses the ethical, technological and economic aspects in a pragmatic, workable manner.

Following lengthy discussions, the European Council adopted its general approach on the AI Act in December 2022. The European Parliament is expected to adopt its negotiating position on the Act in June 2023.

19 | See Voß 2022.
20 | See Europäische Kommission 2021.
21 | See DGB 2021.
22 | See DIN/DKE 2022.

2 Outlooks for the challenge of dual use and the potential of small-scale robotics

This chapter discusses the **outlook for two issues** that were not directly addressed in the expert interviews but are nonetheless relevant to the future development of robotics in Germany.

The first section focuses on the reignited debate about dual-use technologies, i.e. technologies that can have both civilian and military applications. The sea change in security policy as a result of the war in Ukraine, growing tensions with China and increasingly violent conflicts in other parts of the world is raising questions about German **policy on dual-use technologies**. This is likely to have implications for robotics and related technology fields in Germany.

The second section considers the outlook for the **next-but-one robotics generation**. Basic research is already being conducted on systems that could open up completely new areas of application. Robots ranging in size from a few millimetres down to the micrometre and nanometre scale have the potential to bring about disruptive change, especially in the healthcare and biotechnology sectors.

2.1 Civilian and military applications of robotic systems

As well as raising questions about critical dependencies and sovereignty, Russia's invasion of Ukraine on 24 February 2022 and its geopolitical repercussions have also raised normative questions that need to be fundamentally addressed. These include the approach to **dual-use technologies** in Germany's research, innovation and industrial policy.

Dual-use technologies

European commercial law uses the term "dual-use" to refer to **goods that can be used for both civilian and military applications** (Council of the European Union 2009). However, the boundary between civilian and military applications is becoming increasingly fluid in robotics and many other cutting-edge technology fields. For instance, it is relatively easy to convert commercially available **drones** into weapon systems.

On the other hand, the technology also has **potential for deployment in hostile environments** – autonomous systems minimise the risks and can access locations that are difficult for humans to access or remain in for long periods. Applications include exploration, monitoring and defusing devices in deep-sea locations, deployment in highly radioactive environments and in space, and rescue operations in disaster zones. The extent to which the dual-use aspect of autonomous systems in hostile environments is seen as an opportunity or a risk depends on one's political views.[23]

Public research into technologies that could be used for military purposes has been the subject of controversy in Germany for many years.[24] Several publicly funded research institutions have adopted "**civilian clauses**" committing them to only conduct research for civilian purposes. As a result, they do not collaborate with the defence industry. Some of the experts interviewed felt that these "civilian clauses" are outdated in their current form and proposed "**peace clauses**" as an alternative.[25] These would allow public research institutions to participate in projects aimed at **protecting the public** against internal and external threats.

"We should replace civilian clauses with peace clauses."

Some of the interviewees pointed out that military research can bring benefits for civilian applications. Conversely, there are also some areas where **civilian products have more advanced technology** and only need to be modified for military applications.

23 | See Fachforum Autonome Systeme im Hightech-Forum 2017.
24 | See Wörner/Rauch 2022.
25 | See Wörner/ Schmidt 2022; Mohaupt 2013.

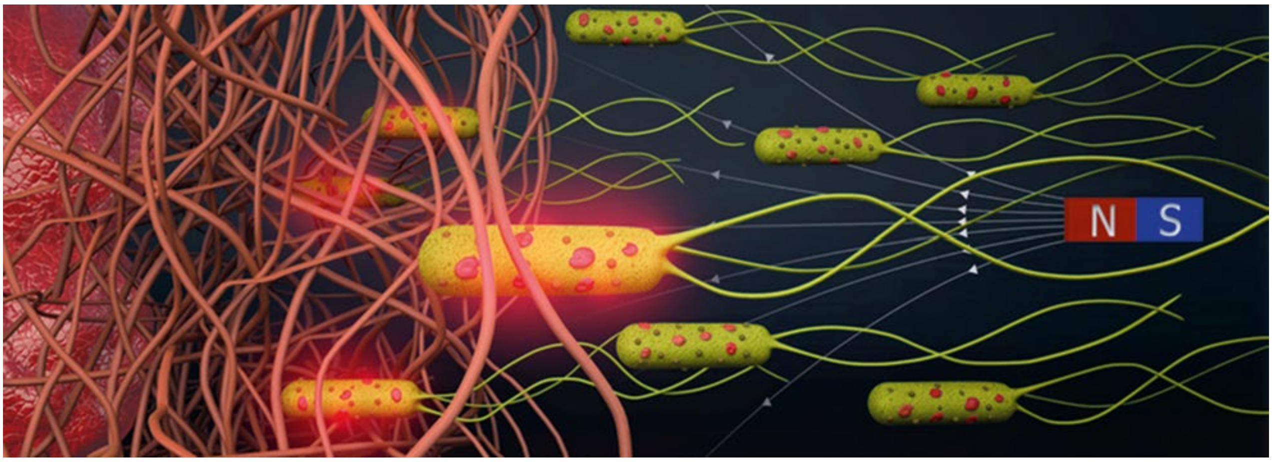


Figure 2: Schematic showing bacterial biohybrid microrobots magnetically guided through fibrous environments (Source: Akolpoglu et al. 2022)

Military procurement policy could support innovation policy in some sectors. However, the experts stress that procurement decisions must always put the equipment's functionality first. The priority for **military procurement policy** is to ensure that the German military is fully able to perform its **statutory duties**.

Conflicts can arise if policy goals other than the needs of the armed forces and security policy requirements are prioritised. These can include the cultivation of foreign relations, securing jobs in economically weak regions or industrial policy promotion of cutting-edge technologies.

The shifting **geopolitical landscape** thus calls for an **open-ended discussion** about the relationship between publicly funded research and the defence industry. In addition to the central ethical questions, this debate – which must include government, science, industry and the general public – should also address the opportunity costs of failing to acquire the relevant technological capabilities. These include the cost of strategic dependency on other countries, for example.

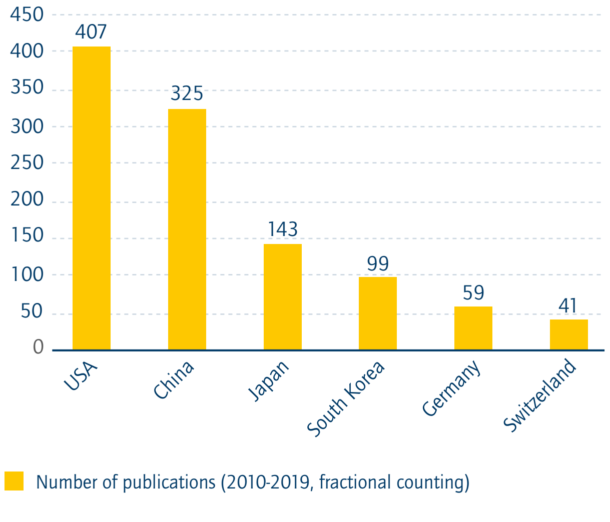
2.2 Future areas of application for robotics

The combination of biotechnology and robotics is enabling **new, personalised treatments for which there is huge medical demand**. Some companies in Germany are developing personalised cancer drugs tailored to individual patients. In order to realise this vision, biotech companies are employing engineers to develop scalable production methods in cooperation with robotics companies.

Research and development of very small robotic systems, known as **small-scale robotics**, is another example of prospective technological developments in this area. Although this field is still largely at the basic research stage, the interviewed experts noted that the standard of scientific research in this area is very high in Germany, which thus has the potential to position itself as a **leading location** in this technology sector if targeted measures are implemented.

Small-scale robotics

Micro- and nanorobots have great economic and social potential. While research in this field is still in its **early stages**, **significant progress has been made in the past 15 years**. At present, the main research focus is on **biomedical applications**. In the future, microbots and nanobots could potentially be used as tools for



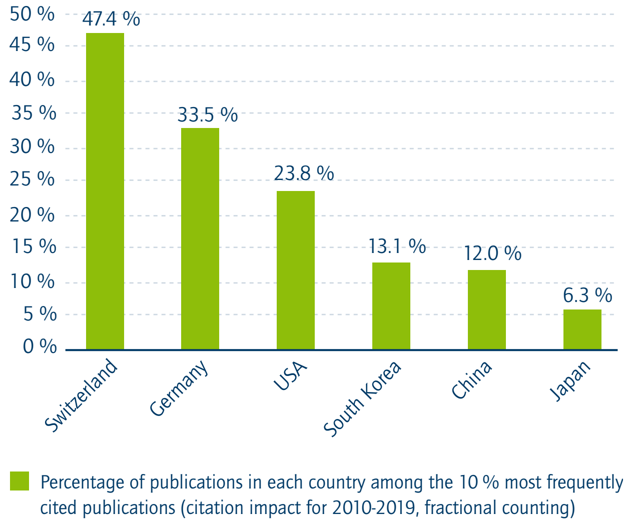


Figure 3: Number of small-scale robotics publications and citation impact of selected countries (Source: Bornmann/Ettl 2022 and in-house database of the Max Planck Digital Library, based on Web of Science)

more targeted **drug delivery** in the target site or for **surgical applications**. If cancer drugs could be precisely delivered to the tumour, their efficacy could be significantly increased and side effects reduced thanks to the drug being concentrated in the diseased tissue.

Small-scale robotics refers to systems at the milli-, micro- and nanometre scale. **Millirobots** are about as big as an average-size insect, **microrobots** are around the size of a human cell, while **nanorobots** are smaller than one micrometre. Researchers have already built nanobots that are the size of bacteria (approximately 800 nanometres) (see Figure 2).

As the size of robots shrinks from the immediately perceptible macro-world to systems at the micro- or nano-scale that are too small to be perceived by human senses, **physical properties** change, and with them the requirements for the robots.

Established engineering techniques cannot be used to move or guide these micro- and nano-systems, since a microrobot has no room for conventional electronic circuits, for example. Nevertheless, these tiny robots can enable **targeted manipulation** at the micro- and nano-scale, for example inside the human body. They can be guided using magnetic fields, ultrasound, light or chemical gradients.

One of the challenges is to “program” intelligence into these machines. **Smart materials** are the key technology in this context and will be crucial to the future success of developments such as controllable actuators, valves and active surfaces. In order to broaden the range of applications for small-scale robots, further research will be needed in the following **four major areas**:

- Locomotion
- **Biocompatibility** and **biodegradability** of the materials used
- **Cooperation** between the robots and **collective control** by human operators
- **Autonomous behaviour** embedded in the physical structure

The realisation of intelligent small-scale robots will also continue to require a **strongly interdisciplinary approach** involving close collaboration between researchers from fields such as materials science, engineering, physics, chemistry, biology, medical imaging, robotics and machine learning. Medical systems should also be developed in close cooperation with clinicians.

According to the interviewed experts, Germany is already making internationally groundbreaking contributions to research in this field. The **quality of academic education** and **high standard of both basic and applied research** were identified as particular strengths.

Germany is extremely well placed to become a leading research location in the field of small-scale robotics. After Switzerland, Germany has the **second highest citation impact**, which is an indicator of the quality of research publications. However, the figures relating to the total number of publications reveal that more research is being carried out in this field in other countries such as the USA, China, Japan and South Korea (see Figure 3).

Insufficient access to venture capital and **limited career prospects** for talented young researchers were among the weaknesses that the interviewees identified in Germany. The growing number of **start-ups** in Germany could at least soon mitigate the lack of job opportunities.

In order for Germany to maintain and build on its strong position in small-scale robotics, the interviewees recommend various measures including simplified **visa rules** for top talents from other countries and **less bureaucratic regulations** for research funding and practice.

3 Analysis of the main strengths and weaknesses of AI-based robotics in Germany

This chapter analyses the **main strengths and weaknesses of AI-based robotics in Germany** in terms of the market and competition, the technology, the innovation and transfer process and the value network. The findings are based on expert interviews, background discussions and visits to centres of excellence, supplemented by a review of the literature.

3.1 Market segments, competition and market environment

The interviewees were unanimous in the view that robotics is one of the **most important key technologies**. Key technology leadership is particularly important for German and European **technological sovereignty** and is thus also highlighted in the BMBF's Future Research and Innovation Strategy.[26]

"Robotics will maintain prosperity in Germany."

Remaining competitive in the robotics market will be key to maintaining productivity and prosperity in Germany. AI-based robotics has particular potential to strengthen the German **economy** and counteract the **shortage of skilled workers** in many industries.

Market segments

Robotics can be broadly divided into four categories. The combination of hardware and AI has disruptive potential in each of these areas of application. In order to maintain and build its competitiveness, Germany must become a leader both in the widespread deployment of AI-based robotics and ideally also in the technology's development.

Due to its broad technological basis, robotics can be used in **many different applications**. These can be broken down into the following categories

- **Service robots** can be divided into mobile and stationary robots:
  - **Mobile service robots** are able to move around, making them particularly suitable for cleaning and construction work, for example. They are also increasingly being used in underwater and hazardous environments.
  - **Stationary service robots** are used for medical and agricultural applications, for example. They assist people with or relieve them from monotonous or dangerous tasks.
- **Driverless transport vehicles**, known as **autonomous guided vehicles** (AGVs), are mainly used to transport goods in the (intra)logistics sector.
- The final category comprises industrial robots and cobots:
  - **Industrial robots**, like stationary service robots, relieve humans from performing certain tasks, helping to carry out traditional industrial assembly line work. For safety reasons, they are separated from locations where humans work by safety fences. This means that they only operate in structured environments.
  - **Cobots** are a special kind of industrial robot that assists human workers with certain tasks. As the intelligence and precision of cobots grows, it is becoming possible for humans and machines to collaborate increasingly closely in a shared space without safety guarding. Many experts from industry believe that cobots will be pivotal to future working methods.[27]

In all of the above fields, the **combination of AI and robot hardware** will lead to new breakthroughs in the relevant areas of application. Innovations in each of these areas will be key to the continued competitiveness of manufacturers and users.

26 | See BMBF 2023.
27 | See Statista 2021.

The economic importance of robotics: total and projected sales

The use of AI-based, adaptive robotics in unstructured environments is a key competitive factor in the transformation of Germany's manufacturing base. Robotics-based automation is a core element of profitable Industrie 4.0 models and must therefore be embraced by German companies, especially SMEs.

Robotics is already an **economically important** industry and its significance is set to grow further still. Global **annual sales** in the robotics market are projected to reach **around 40 billion US dollars** in 2023. **Service robots** are expected to dominate the market by the end of the current decade.[28] The projected trends for industrial and service robotics are shown in Figure 4.

By 2030, the market for service robots could grow to as much as **170 billion US dollars**, potentially double the size of the **90 billion US dollar** market for **industrial and logistics robots**.[29] The deployment of robots in **unstructured environments** will play an increasingly central role. Because AI enables intelligent, adaptive learning, it will be hugely important in this context.

Intelligent production automation is a top priority for maintaining prosperity and securing the competitiveness of German industry. The more widespread deployment of AI-based robotics in both **production** and **intralogistics** is key to the success of **Industrie 4.0**. The experience gained in the industrial sector can help to leverage the huge potential of service robotics. Technology spillover effects can be expected to benefit service robotics, especially in the construction and agricultural sectors, but also in household, care and search and rescue settings. However, the following sections focus mainly on industrial robotics.

Industrial robot manufacturers

While most of the global market leaders in industrial robotics are Japanese, Chinese providers are becoming increasingly important market players. This trend should be closely monitored in the context of economic and innovation policy initiatives to strengthen Germany's strategic sovereignty, in order to prevent critical dependencies. Most German manufacturers are SMEs that have become successful players in individual niche robotics markets.

The leading global industrial robotics manufacturers are **Fanuc, Yaskawa, Epson, KUKA, Estun and ABB**. The market is dominated by Japan, but more and more Chinese providers are forcing their way in.

Industrial robotics manufacturers in **Germany** fall into **two broad categories**. Production is still dominated by **large corporations** in the automation and logistics sectors such as Dürr, Bosch Rexroth, Jungheinrich, KUKA, Linde and SSI Schäfer. However, there are also **several small and medium-sized robotics specialists**.

These companies have become **world-leading robot suppliers** in specific niche markets.[30]

Over **three quarters of the 50 largest industrial robot manufacturers** in Germany specialise in the development and production of a **specific type of robot**. Most of the companies analysed make AGVs, six-axis articulated robots or linear robots.

An analysis of the geographical distribution of Germany's top 50 industrial robot manufacturers reveals a clustering pattern. More than three quarters of these companies are headquartered in the states of Baden-Württemberg (30 percent), Bavaria (28 percent) and North Rhine-Westphalia (20 percent).[31]

28 | See BCG 2021.
29 | See BCG 2021.
30 | See Meyer Industry Research 2020.
31 | Ibid.

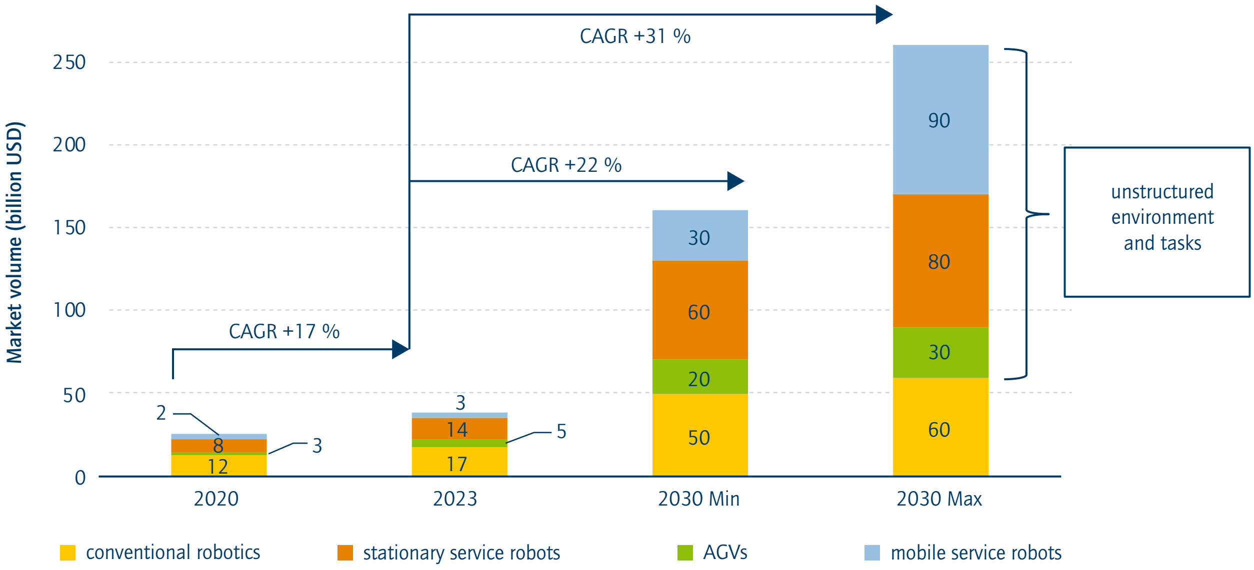


Figure 4: Projected market trends for service and industrial robotics; CAGR = compound annual growth rate (Source: authors' own illustration based on BCG 2021) Global industrial robotics market shares (Source: authors' own illustration based on Statista 2021)

Germany's share of the global user market for industrial robotics

China alone accounts for almost half of global demand for industrial robots. Although Germany is still one of the world's top 5 user nations, the number of new installations is stagnating, while it continues to grow in other economic areas.

The **total industrial robotics market** was estimated to be worth approximately **15 billion US dollars** in 2022. Apart from **China**, the four other countries that dominate the global market are **Japan,** the **USA, South Korea and Germany** (see Figure 5).

In total, **approximately 520,000 new industrial robots** were installed worldwide in 2021. This represents a **growth rate of 31 percent** year-on-year. The stock of operational industrial robots around the globe has now reached a new record of about **3.5 million units**, having doubled in the space of just six years.[32]

Following a brief decline during the Covid-19 pandemic, the number of new installations in the USA and Asia is now rising again. Over the past few years, **China** has established itself as the **global leader** in new industrial robot installations. The **number of new installations has grown by 72 percent** in China since 2015, whereas it has **stagnated in Germany for several years now**. In 2021, half of all new industrial robot installations worldwide were in China, while just 4.5 percent were in Germany.[33]

It is estimated that China bought almost 6.7 billion US dollars worth of industrial robots in 2022. As well as accounting for **44 percent of global sales**, this means that **China** is investing **ten times** as much as Germany in new industrial robots.[34]

32 | See IFR 2022d.
33 | See IFR 2022c.
34 | See Statista 2021.

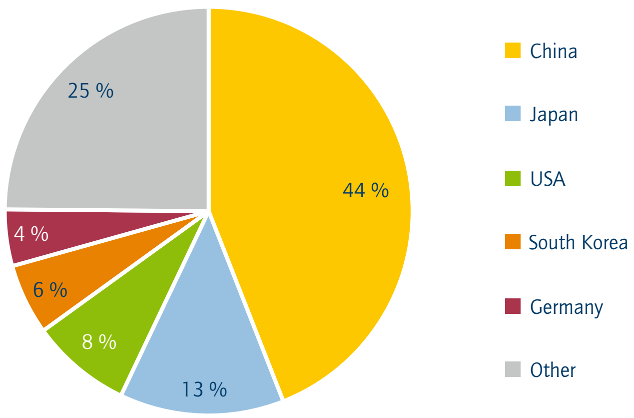


Figure 5: Global industrial robotics market shares (Source: authors' own illustration based on Statista 2021)

Industrial robotics user industries

While the main industrial robotics users internationally are the electronics and automotive industries, in Germany only the automotive industry falls into this category. Intelligent robots are opening up new areas of application in both industries. They are also enabling the widespread use of robots for the first time in other sectors, especially those with unstructured work environments.

Globally, the two biggest users of industrial robots are **electronics and automotive manufacturers** (see Figure 6). Together, these two sectors account for **almost half of the global industrial robot market**, although their dominance is declining.

High-precision manufacturing is essential in the electronics and automotive industries. Both are thus ideally suited to conventional automation using traditional robots that can only operate in **structured environments**.

However, demand for traditional industrial robots is being accompanied by growing interest in **collaborative robots**. In 2018, just under 5 percent of the 375,000 industrial robots installed around the world were cobots.[35] This percentage had already tripled (to 13 percent) by the end of 2022 and is set to keep growing.[36] It is forecast that **over 50 percent of manufacturing companies** will integrate collaborative robotics into their operational processes within the next decade.[37]

New generations of robots that can be deployed in **unstructured environments** will open up **new areas of application**, for example in the food, plastic and chemical industries (see Figure 6) and increasingly also in sectors such as agriculture, construction and nursing and healthcare.

In the international market, **global high-tech companies** carrying out moonshot projects in the field of AI-based robotics are emerging as competitors to established providers. Alphabet launched its subsidiary Intrinsic with the aim of conquering the industrial robotics market. Alphabet also has ambitions to enter the intelligent domestic robot market through its Everyday Robots subsidiary. Meanwhile, Xiaomi and Tesla are developing humanoid robots, and Hyundai has acquired Boston Dynamics and invested 400 million US dollars start-up capital in an institute for the development of advanced robots. In recent years, US companies including Alphabet, Microsoft and Amazon have established offshoots of their research organisations in cities such as Munich, Tübingen, Berlin and Zürich, offering staggeringly high salaries in order to recruit outstanding young talents.

35 | See IFR 2020a.
36 | See Statista 2021.
37 | See IFR 2020b.

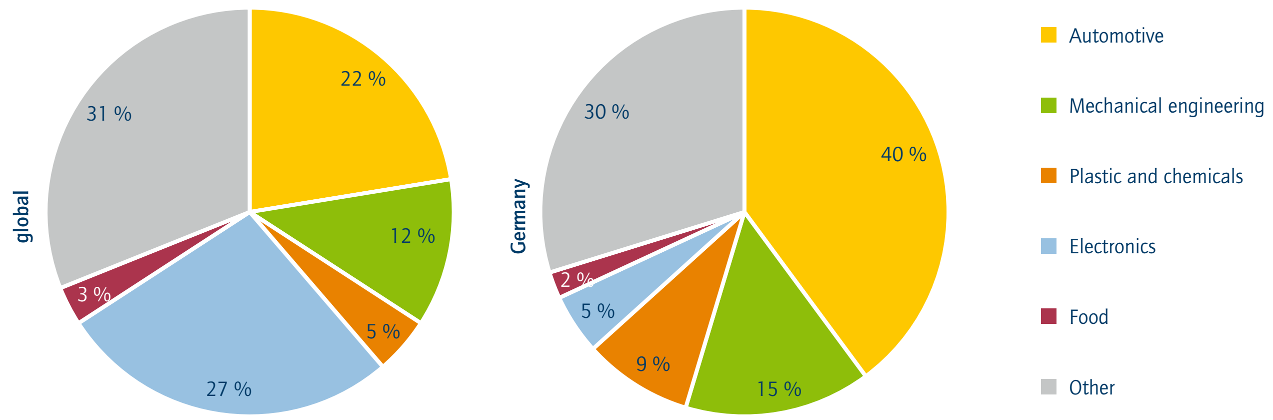


Figure 6: Industrial robotics user industries globally and in Germany (Source: authors' own illustration based on Statista 2021)

3.2 The technology: from automatic machines to intelligent, self-learning systems

The field of robotics is undergoing a profound transformation. Increasingly, robots are acquiring the ability to cope with changing, unstructured environments and perform more challenging tasks. A breakdown of its technological components reveals AI-based robotics to be a deep tech innovation. Germany's strengths lie in its strong user base and some areas of research. In order to enable AI-based robotics, it will be particularly important to ensure the sufficiently widespread rollout of digitalisation.

Traditional robot systems are mostly used for pre-programmed, repetitive **movement sequences in structured environments**. However, significant advances in robotics and AI research are rapidly and fundamentally transforming this picture. There is now a clear trend towards complex, highly autonomous, AI-based robot systems that can perform **challenging tasks in unstructured environments** and use machine learning techniques to continuously adapt, while also being easier to use.

> "Future robotic systems should be as easy to use as a smartphone."

For instance, robot arms that learn how to feel can achieve extremely high positioning accuracy when performing assembly tasks. Mobile transport platforms are also becoming user-friendlier thanks to their ability to highly autonomously map new environments, detect changes and adapt to them autonomously during operation.

This new generation of robots is known synonymously as intelligent, AI-based or cognitive robotics. Since this trend includes the full spectrum of robot types and applications, it is hereafter simply referred to as **AI-based robotics**. This should be understood as a simplified umbrella term that encompasses hardware advances and topics where AI only plays a peripheral role. Figure 7 divides an AI-based robot system into five basic elements that are further broken down in Figure 8.

- **Element 1** (top left)**:** A system's design must be based on the **requirements of real-world applications**. This step is vital to ensure the effectiveness of targeted innovation, since it aims to prevent technological developments that overlook market needs. That said, untargeted innovation based on basic research is also important, especially in the longer term.
- **Element 2** (bottom left)**:** Intelligent robots are very different to traditional systems due to the much **greater importance of software and data**. Complex robot systems have hundreds of thousands of lines of code. **Machine learning techniques** that involve processing large volumes of data are increasingly important in many functional components. These systems are often developed by large teams of software engineers,

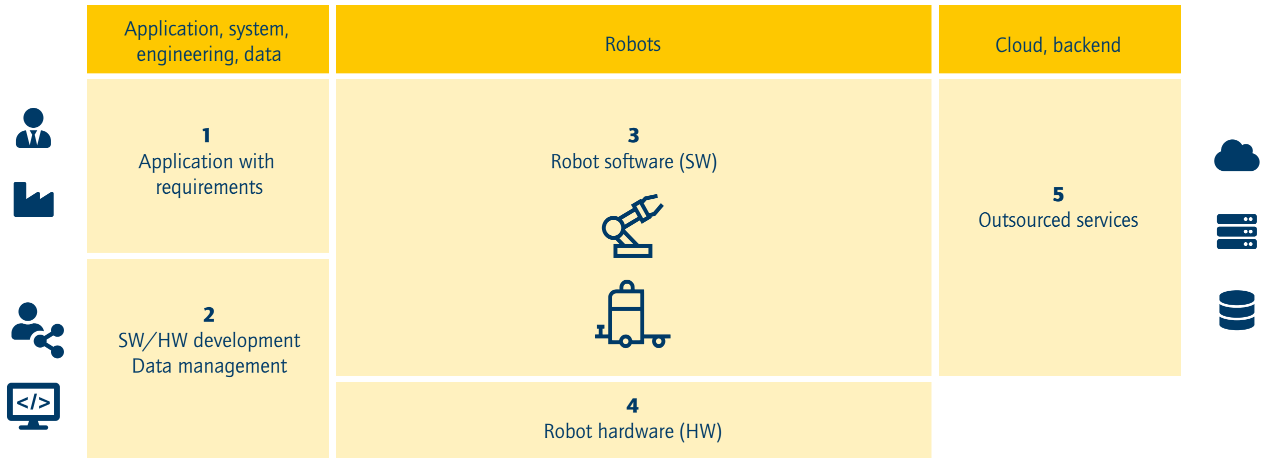


Figure 7: Basic breakdown of AI-based robotics systems (Source: Robert Bosch GmbH 2022)

algorithm experts and system specialists with access to a modern tooling landscape. As well as processing real-world data, they increasingly also use **simulations** in which very realistically simulated robots perform their tasks in simulated environments.

- **Element 3** (top centre)**:** All intelligent robots share a number of **basic functional components** that are extremely research-intensive and are key to market differentiation:
  - **Perception** (fusion) involves the use of sensors that allow robots to perceive their environment and detect obstacles, objects or people.
  - **Simultaneous localisation and mapping** (SLAM) allow mobile robots to map a new environment and keep track of their location within it (i.e. their position on the map). The map model also has other functions, for example as a digital twin or in human-machine interaction.
  - **Planning** is the foundation of intelligent behaviour. Examples include motion planning (how does a robot get from A to B?), action planning (what is the best sequence of actions to achieve the desired goal?) and coverage path planning (which sequence of movements can fully cover the area of interest without any gaps?).
  - **Motor skill learning** refers to the acquisition of individual skills such as gripping, fitting together and inserting for assembly robots or manoeuvres such as docking, following and edge cleaning for mobile service robots. These skills can then be combined into goal-oriented action sequences through planning or learning.
  - **Motion control** allows robots to perform the optimal movements for the task at hand using actuators such as electric motors in robot arms.
  - **Human-robot collaboration/human-machine interaction** (HMI) refers to the ability to interact and cooperate with humans. This is becoming increasingly important, since ease of use is critical e.g. for SMEs that don't have their own in-house robotics integration engineers.

The function blocks contain **system layers** (shown in detail in Figure 9) that are key to ensuring that robots can be deployed safely, scalably and synergistically in a range of applications. Open-source initiatives are establishing new standards in these layers, such as the ROS robotics middleware that is now widely used around the world.

Robot safety is critically important. The regulatory framework and relevant standards must be continuously updated to reflect robots' growing capabilities. Extensive research is needed in this area, for example to develop standardised inspection and testing methods that work in a wide range of different contexts.

- **Element 4** (bottom centre)**:** The **hardware** encompasses the full spectrum of robots – from microrobots and elastic manipulators to mobile cleaning machines and robotic arms for heavy loads. All of them are built with sensors, actuators and embedded, networkable processing units. Robot hardware is also a research-intensive field. Research topics include the development of new **sensor principles**, **material properties**

(soft robotics) and **scaling domains** (microrobotics/nanorobotics). Chapter 2 takes a specific, in-depth look at the last of these topics.
- **Element 5** (right)**:** The voice recognition feature on modern smartphones runs in the **cloud** (i.e. external data processing structures) rather than on the device itself. In a similar trend, CPU-intensive AI algorithms and other central services such as fleet planning are also increasingly being outsourced. Furthermore, robot sensors generate large volumes of data that are important for the continuous improvement of many AI-intensive components and provide information about operation in the field or customer needs.

"Germany can still achieve lift-off in the deep tech sector."

The tremendous complexity of this technology field means that AI-based robotics can be classified as a **deep tech innovation**. Deep tech refers to deep technologies with high disruptive potential. Deep tech innovations are research-intensive, and their implementation is associated with high technology risks and thus also **high commercial risks** and long payback periods. Other examples of deep tech include quantum computing, autonomous driving and digital health.

According to the interviewees, **Germany has the following strengths and weaknesses** with regard to the technology:
- As an industrialised nation, Germany's **strengths** include access to customers and markets and key know-how in a range of application domains. Other advantages based on these strengths include the proximity of suppliers and users and a good understanding of real market requirements. However, this picture is changing as outlined in Chapter 3.1. Application domains such as electronics, where other economic areas are the leading robotics users, are becoming increasingly important.
- The main **weaknesses** identified by the interviewees relate to **digitalisation**. They range from the continued low penetration among SMEs (see Chapter 1) to the failure to train and recruit enough software, data and cloud engineers with a state-of-the-art understanding of the infrastructure and tooling landscapes. Many digital networking technologies such as cloud services are monopolised by US and Chinese IT companies. And in many cases, the regulatory framework is not nuanced enough for the data economy.
- While German robotics software and hardware **research** rates as better-than-average compared to other countries around the globe, there is still **room for improvement**. Targeted strengthening of research and talent acquisition and structural improvements to university research facilities are key to achieving technology leadership and securing long-term competitiveness. Chapter 4.2 discusses these aspects in more detail.

3.3 Value network

In simplified terms, the **traditional** robotics **value chain** comprises robot manufacturers, systems integrators and end users. The robot manufacturers sell the hardware – such as manipulator arms or mobile platforms – together with the control system and basic functionality. The systems integrators integrate the robot and any necessary safety or process components into the user environment where the user then operates their robotic system.

In some cases, not all the actors are involved, for example if several roles are performed by a single company or if the user has extensive automation expertise and doesn't need an integrator, as is the case with the large automotive companies.

However, this rigid chain is increasingly transforming into a more flexible **value network** with space for new actors and partnerships (see Figure 9). Open interfaces, standardisation and specialisation are driving the emergence of a new market for robot components sold via new **marketplaces** such as the UR+ Store of Universal Robots, Denmark's leading collaborative robot manufacturer.

There is particularly strong demand for technologically advanced components such as AI-based perception systems and smart actuators.[38] Moreover, data- or service-based **business model innovations** such as Robot as a Service (RaaS) are opening the door to new concepts of operations and actors.

38 | See Interact Analysis 2021.

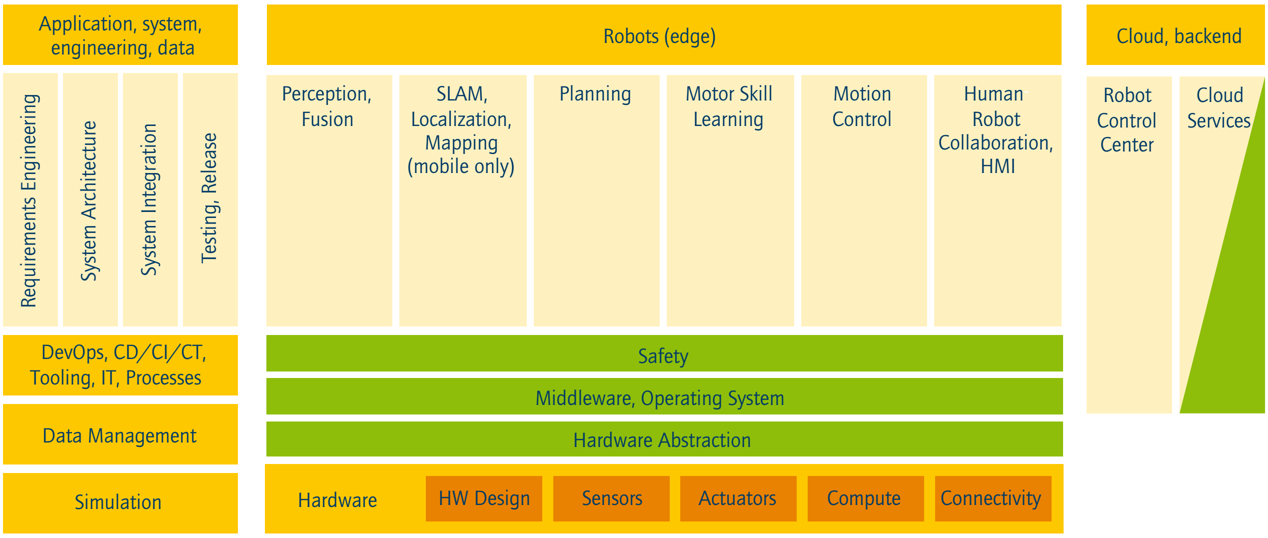


Figure 8: Detailed breakdown of AI-based robotics systems. The illustration shows the full picture, but not every system will necessarily include all the components. Typically, development no longer ends with the sale of the device but is ongoing – data from the field is fed back into the processes for requirements engineering, SW development and enhancement of AI-based robot capabilities (Source: Robert Bosch GmbH 2022).

The roles within the robotics ecosystem (see Figure 9) and Germany's **strengths and weaknesses** are outlined below:

1./2. Component suppliers: Germany is traditionally strong in the mechanical engineering and mechatronics sectors and also has an abundance of start-ups that make hardware and software components for robotic manipulators and mobile robots. Innovative young firms are benefitting hugely from simple market access via new marketplaces (such as UR+ Store and Franka World). It is important for them to engage in co-creating standards and participate in the value creation of the emerging marketplaces.

3. **Robotics OEMs:** Start-ups and medium-sized collaborative robot arm and AGV/AMR transport platform manufacturers are shaking up the market. Together with Chinese competitors, they are putting significant price pressure on established original equipment manufacturers (OEMs). Meanwhile, large players are building a position in the market through acquisitions. With Germany's sole large robotics OEM, KUKA, now under foreign ownership, industrial policy measures are needed to safeguard this key role in the ecosystem through the establishment of new actors. While the lack of a German OEM is not directly problematic for the user industries as long as they have good access to foreign suppliers, a German OEM is undoubtedly desirable from a sovereignty perspective.
4. **Systems integrators:** While Germany is well equipped in terms of production and logistics for the traditional automation business, these companies need to embrace the transformation being brought about by digitalisation, the data economy and AI-based robotics. New skills and specialists such as computer vision engineers will be needed in large numbers.[39] Systems integrators that succeed in adapting can drive innovation and profit from the transformation. User-friendly modular solutions can help them venture into new applications that were previously unprofitable. The challenges also include opening up new areas of application for robots in sectors where the end user environments are particularly challenging, for example the construction and healthcare industries.
5. **Operators:** New data- or service-based business models will present particular challenges. This will create an opportunity for operators to take on a new role after a system is purchased by assuming responsibility for the efficient operation of the robotics service in a given area of application. Their strategic importance and share of value added will depend on how access to field data is shared within the ecosystem.
6. **(End) users:** As an industrialised nation, Germany's traditional strengths are as a user of robotics systems in production and logistics, as well as its access to markets,

39 | See IFR 2020b.

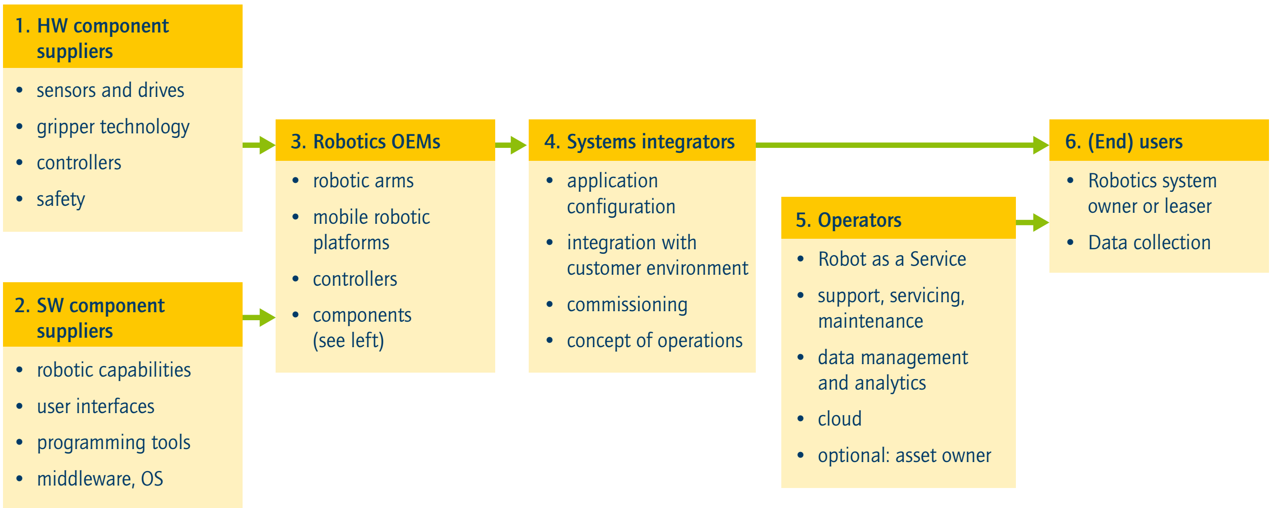


Figure 9: The modern robotics value ecosystem. The rigid traditional robot manufacturer – integrator – user chain is transforming into a more flexible model with space for new actors. This model enables the emergence of strategic control points such as component marketplaces or differentiating AI-based robotic capabilities. Larger companies can perform several of these roles at the same time. (Source: Robert Bosch GmbH 2022)

customers and critical domain knowledge. The integration of AI-based robotics is confronting users in every sector with new challenges associated with changing job profiles and skill requirements. Moreover, the level of digitalisation expertise and risk appetite for the implementation of AI-based robotics varies significantly in new areas of application where demand for automation is forecast to rise, such as construction, agriculture, healthcare, pharma, the household sector and the circular economy.

As discussed in Chapter 3.2, AI-based robotics is a **deep tech** innovation. In other words, it is a research-intensive technology with **high disruptive potential**, its implementation is risky and its payback periods are long. At present, most of the value network players in Germany, even the large enterprises, are unable to bring this technology to market at scale and become a new global AI-based robotics OEM. Consequently, **national innovation policy measures** will be required if Germany is to become a global leader in robotics.

3.4 Innovation and transfer process

Germany has a broad and strong innovation landscape. With deep tech innovations like AI-based robotics, the transition from proof of concept to industrialisation and scaling is critical. A user industry pull effect is required to provide a practical market perspective that enables an effective, targeted transfer process from research to application.

The innovation and transfer process aims to rapidly turn good ideas into profitable new products and services. Especially for research-intensive technologies like AI-based robotics, it is a very challenging and lengthy process involving multiple actors. Figure 11 depicts the **typical stages in the innovation and transfer process**.

With its strong university and non-university research institutions, large enterprises, start-ups and world-class SMEs, Germany is well positioned in all the relevant areas. However, successful **technology transfer** requires more than this. It calls for ideas that address a **real need** at the **right time** and are **adequately funded** and outstandingly implemented.

According to the experts, it is also necessary to overcome certain cultural barriers. They identified big gaps between research and industrial application. While businesses think that researchers often **fail to understand the needs of industry**, researchers feel that many companies are **too reluctant to innovate**.

Transitions and overall framework

In order to improve collaboration between the different actors, it is necessary to consider both the transitions and the overall framework of the transfer process. Start-ups are discussed separately below.

- **Transition 1:** Universities, universities of applied sciences and non-university institutions (the Max Planck Society, Fraunhofer Society, Helmholtz Association and Leibniz Association) provide good coverage of the entire spectrum from pure basic research and applied basic research to application-oriented development. This transition can thus be categorised as relatively smooth. Germany has particularly strong actors engaged in transferring applied research results to users. The Fraunhofer Society, for example, also acts as a research service provider for SMEs. However, especially in the fields of AI and robotics, **there is no longer a strict division of labour** between publicly funded basic research and privately financed applied research.

> "Companies must want to engage actively in research and see themselves as part of the research community."

- **Large**, capital-rich **corporations**, **including many US platform enterprises, carry out their own applied basic research**. They are able to attract many of the best talents by offering higher salaries, better research infrastructure and the prospect of turning scientific discoveries into innovations. Publicly funded research in Germany must find answers to these recent developments if it wishes to keep competing with leading locations in Asia and North America.
- **Transition 2:** This is often the point where research meets industry and technological solutions meet market needs. Various funding programmes and public-private partnerships such as the BMBF Research Campus provide opportunities for the different actors to come together and form partnerships. These typically lead to proof-of-concept studies aimed at showing that a prototype product can meet its intended application's critical requirements. While this stage is often critical, it does not mean that a development is ready-for-market.
- **Transition 3:** The journey from proof of concept to a successful product in the market is long and both knowledge- and capital-intensive. The prototypes must be developed into a robust, high-quality, certified product that can be produced at scale, meets users' expectations and is also profitable. For research-intensive, potentially disruptive technologies like AI-based robotics, this requires considerable commercial foresight, risk appetite and perseverance. This transition is the **greatest weakness** in the German innovation process, as is apparent in various respects:
  – Start-ups encounter hesitant SMEs that have had mixed experiences with digitalisation projects.
  – Universities develop new technologies for large enterprises that would provide them with a strong point of difference in the market. But these technologies are deprioritised in favour of less risky innovations in neighbouring business areas.
  – Fraunhofer institutes develop outstanding prototypes for partners who have recognised the urgent need to automate but are reluctant to make the investments required to develop their own robotics expertise for the prototypes' industrialisation.

The overall **framework** is also key to a successful transfer process:

- **Innovation policy:** As highlighted in the latest *Commission of Experts for Research and Innovation (EFI)* report on *Research, Innovation and Technological Performance in Germany*, Germany's innovation policy system is in need of strategic development. The incremental product innovations that have secured Germany's prosperity in recent decades are no longer enough to achieve transformative change. The report recommends an **agile, mission-oriented** innovation policy that sets targets which are followed up through regular evaluations[40].
- The Commission of Experts also calls for key technologies (including robotics) to be strengthened. The experts interviewed argue that strengthening Germany's robotics industry will mean dropping the "watering can policy" of lots of small, widely scattered investments. Locations that already have a strong global position in the relevant disciplines have a better chance of establishing themselves as internationally competitive **robotics hubs**. Accordingly, science and technology policy should aim for a smart mix of flagship funding and more widely distributed funding in order to strengthen the whole of German industry.

40 | See EFI 2022.

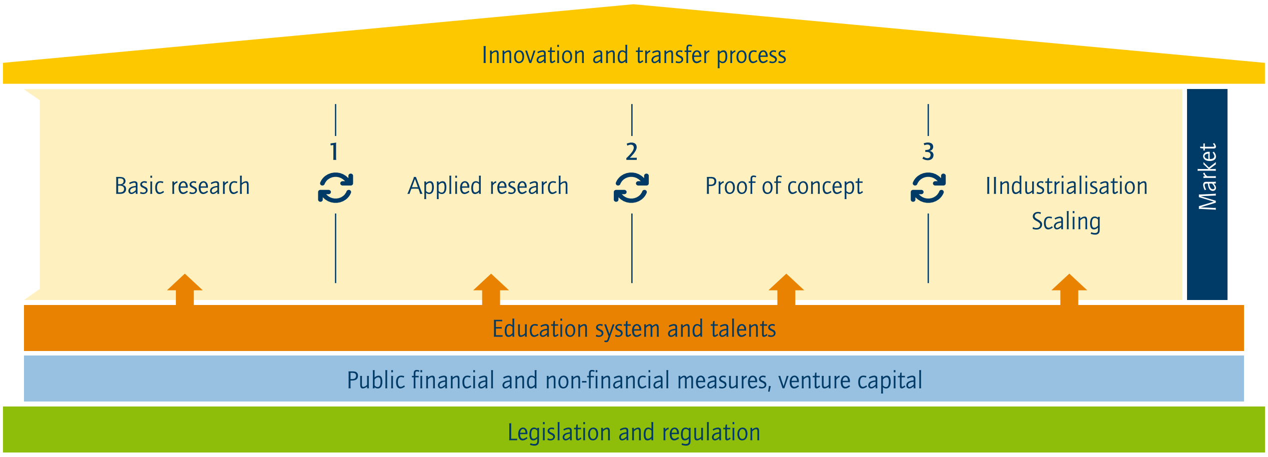


Figure 10: Innovation and transfer process. Ideas from basic research progress through the applied research and proof of concept stages before their eventual industrialisation in the market. Their technology readiness level increases as they go through transitions 1 to 3. Many existing support measures, especially public-private partnerships, are geared towards bringing research and business actors together at transition 2. However, this study shows that, because of the high commercial risks and long payback periods associated with AI-based robotics, the weakest part of the process is actually the industrialisation and scaling stage (transition 3). (Source: Robert Bosch GmbH 2022).

- **Regulation:** Innovative robot safety regulations that build on national and international norms, testing standards and certification expertise would provide a strategic control point and give German market players a concrete competitive advantage. Specifically, this would mean developing inspection and testing methods aimed at creating a basis for guaranteeing occupational safety and for legal certainty and clarity regarding liability for AI-based robots placed on the market.
- The AI dimension presents additional challenges such as ensuring safe machine learning, data security and data access rules and safe interaction. The regulations should be developed for stationary and mobile robots across all sectors. This will require the strategic development of an effective international **standardisation and certification body**. Failure to do this will leave Germany at risk of falling behind in the key technology of robot certification, especially in view of the huge efforts and investments that China is making in this area. This requirement can be addressed through the BMWK regulatory sandbox concept, which provides the freedom to test innovations in real-life conditions under the supervision of the regulator.
- **Education system and talents:** The importance of a sufficiently high quantity and quality of robotics and AI talents was already alluded to in Chapter 4.2 and is discussed in more detail in Chapter 5.2. The key challenge will be to meet the need for young robotics talents at every stage of the innovation process (see Figure 10) and from right across the spectrum of tertiary education in Germany – from budding top researchers with doctorates and post-doctoral qualifications and people with Master's and Bachelor's degrees from universities and universities of applied sciences to specialists holding technical college qualifications with a strong practical focus. Vocational training institutions must also provide more practical robotics qualifications.

Start-ups and venture capital

The **German robotics start-up** landscape spans everything from new robotics OEMs producing cognitive collaborative robots or autonomous transport platforms to suppliers of components for gripping unknown objects and intelligent robot fleet control.

As with other young deep-tech companies, the challenge for robotics entrepreneurs is the greater-than-average **duration and cost** of developing their products. This is exacerbated by **Germany's weakness** in relation to venture capital. On average, venture capital investments in Germany are 2.7 times lower than in the

UK, 4.1 times lower than in the US and 5.2 times lower than in China. Studies have already pointed out that this is not an ideal environment for manufacturing and robotics start-ups.[41]

To date, a reasonable number of robotics start-ups have managed to obtain significant levels of **finance**. Agile Robots has become Germany's first robotics unicorn. Wandelbots, Fruitcore and Micropsi are among the other start-ups to successfully conclude their funding rounds in the past year. Active investors in robotics start-ups include tech investors, investment companies, private equity firms, venture capital funds, business angels, family offices and Chinese corporations.

The venture and growth capital that is available in Germany focuses primarily on the seed and exit stages of start-ups and growth companies. This results in a **critical investment shortfall during the growth stage** that is mainly made up with foreign venture capital. As well as potential security issues, this reliance on foreign investors due to the **lack of domestic capital** also means that there is a danger of losing know-how and talents and even of entire companies relocating to other countries.

Young robotics start-ups struggle to acquire **German SMEs as customers**. While the shortage of skilled workers is increasing the pressure on SMEs to automate more of their production processes, many AI-based robots fail to provide the easily scalable turnkey solution they are looking for. A **lack of venture capital and scaling expertise** means that many young companies fail to make the transition from proof of concept to a concrete product.

Other German weaknesses cited by the interviewees include **over-regulation** and unfavourable legislation with regard to R&D capital allowances and remuneration in the form of company shares.

41 | See KfW Research 2020.

4 A robotics strategy

The previous chapter highlighted the importance of AI-based robotics for German industry and its market potential. It discussed the direction of the technology's future development and the elements in the innovation and transfer process that are key to successful industrialisation.

In this chapter, the conclusions are used to formulate a strategy to help Germany **achieve** the overarching **competitiveness, technology sovereignty, resilience and sustainability goals**.

The **user orientation and incentivisation strategy** described here constitutes a targeted proposal for meeting the challenges associated with AI-based robotics' specific transfer barriers, especially during the final stages of bringing a product to market. It is thus intended as a **complementary management tool** that should go hand in hand with strong public **support for basic robotics research**, which remains as essential as ever.

4.1 Strengthening competitiveness through user orientation

In view of the significant market, technological and transfer process challenges, an economic incentive is needed for users in order to create a pull effect. The goal of making Germany a leading user of AI-based industrial and service robotics holds tremendous value-added potential and also fulfils the innovation policy requirements with regard to technological resilience, demographic change and sustainability. Germany's outstanding Industrie 4.0 expertise and strong domain knowledge increase the chances of successful implementation. In parallel with the scaling of automation across the whole of German industry, economic and innovation policy measures should therefore be implemented to support the ongoing development of future robotics systems.

Germany will only be able to play a part in the future of robotics as an industrial and manufacturing location and protect its **sovereignty** if it has reliable access to the necessary technologies and skills in Europe.

As already discussed in the market analysis in Chapter 3.1, the industrial robotics industry in China is growing very strongly. Thanks to the complete buyout of KUKA and the acquisition of majority stakes in several German robotics start-ups (including Neura Robotics and Germany's only robotics unicorn, Agile Robots), **China** is also becoming an increasingly important player in the German robotics industry. The interviewed industry representatives do not believe the current situation to be critical. However, they recommend that this trend should be closely monitored so that **prompt measures can be taken to counteract it** as and when necessary.

Germany can build on its **strengths in research**, hardware development based on **traditional engineering know-how** and **strong domain knowledge** in its industrial sector to unlock the huge economic and strategic potential of AI-based robotics and protect its technological sovereignty in manufacturing industry. While its Industrie 4.0 expertise provides a good basis for increasing the level of automation, this expertise must be strengthened still further. The importance of Industrie 4.0 and the need for AI-based robotics to enable its scaling are discussed in detail in Chapters 1 and 2.

However, it will take much more than this to build a sustainable competitive position in the AI-based robotics sector. As with other deep tech innovations, government, science and industry must work together and coordinate their measures. This is key to achieving the common goal of a **strong robotics ecosystem**. It is up to the German government to create an internationally competitive innovation policy framework that allows this ecosystem to flourish. The most effective instruments in this context are market- and user-oriented incentives that trigger a pull effect and **incentivise the use of this technology**.

Support for users should be linked to market success. Since this can only be achieved by cooperating with other partners, users will be motivated to **bring together the necessary expertise in a consortium** and provide the participants with sufficient financial resources. It is also necessary to ensure that financial resources are made available as quickly as possible, since start-ups and smaller SMEs are particularly reliant on them. This can be done through project funding for the consortium members, for example.

"Too many people in Germany are wrapped up in their own little projects. But successful market penetration will require them to join forces."

These consortia focused on the market-oriented use of the technology and comprising innovation providers including start-ups, SMEs and large enterprises are referred to as "**robotopes**". Multiple robotopes can provide the basis for a strong robotics ecosystem in Germany. As well as being key to the establishment of a leading user market, this ecosystem could provide a focal point for the emergence of a globally competitive robotics OEM. This is illustrated by the case of Universal Robots. Emerging from the Odense ecosystem in Denmark, it has grown from a small innovation provider into the global market leader for cobots.

To support Industrie 4.0 and Germany's competitiveness, robotopes should initially be established for **production applications**. Thanks to the strong synergies in the technological architecture, it would then be relatively easy to transfer AI-based robotics to other applications. **Intralogistics** is another key sector where user-oriented robotopes should be prioritised, while there are also promising applications in agriculture and construction. Early applications for **human-centred (service) robotics** should also be addressed. A global competitive advantage can be gained if the development and operation of robotopes is accompanied by measures to **develop innovative regulation and standardisation**.

As well as increasing competitiveness, ensuring resilient value chains and strengthening technological sovereignty, robotopes also aim to **support the United Nations Sustainable Development Goals (SDGs)**. According to data published by the International Federation of Robotics, the use of robots can play an important role in achieving 13 of the 17 **SDGs**.[42] For instance, robots can replace chemical weeding agents in agriculture or reduce resource consumption in cities by helping to recover materials. The theme of robotics and sustainability is discussed in more detail in Chapter 1.

4.2 World-class research, teaching and talent acquisition

The discussion of AI-based robotics technology in Chapter 3.2 points to a strong need for research in this field. The development of unique selling points to secure the long-term competitiveness of German players will call for world-class research. This should be strengthened in a targeted and collaborative manner at existing centres of academic excellence. In addition to research, university teaching and vocational training are also vital to enabling recruitment of a sufficiently large number of highly qualified robotics and AI talents. Moreover, it will be crucial to significantly reduce the very high numbers of talents currently leaving Germany to work elsewhere.

To ensure its **technological sovereignty** and take a significant share of AI-based robotics value-added, Germany must also be a leader in basic research and development.

"Germany must become a robotics developer.
We can't leave the development to others."

World-class research in AI-based robotics will need to be accompanied by a higher education system that attracts and retains top talents from around the world through teaching excellence. Research should have a strong focus on the **interdisciplinary combination of AI and robotics**, combining Germany's strengths in traditional mechanical engineering and hardware development with the wealth of data available thanks to its position as a leading industrial location.

In terms of implementation, existing **robotics research centres of excellence should be strengthened**. Rather than operating in isolation, however, they should form consortia in order to create synergies, reduce overlaps and apply jointly for **long-term research and application projects**. The aim should be to secure the technology's strategic control points and enable German industry to achieve ownership of the strategic control points in the value network. The projects should strike a good **balance between untargeted innovation** (pure basic research) **and targeted innovation** (everything from applied basic research to application-oriented development).

42 | See IFR 2022b.

While German robotics research compares favourably with other countries around the world, it is nonetheless largely failing to fulfil its potential. This is mainly due to the often **rather unattractive research conditions and career paths at German universities**. The weaknesses in the German research landscape cited by the interviewed experts include the extremely high teaching load of university professors in Germany, salaries that do not reflect market rates, and barriers to students spending longer periods doing research in industry, as is customary in the US. This predicament is not just a missed opportunity in terms of competing with other research locations around the world – by affecting teaching standards, it is also damaging the training of the next generation of robotics and AI talents.

Another key to success is the availability of a sufficiently **large number of highly qualified robotics and AI talents**. Similar skills are required in other AI domains such as autonomous driving. This is giving rise to a situation where there is **huge demand** in the labour market but only a very limited supply. Research institutions, start-ups, established manufacturers, systems integrators and users are all affected in equal measure.

It will take a major effort to close this demand gap. In addition to **better** (vocational and university) **education**, Germany must become an **attractive location** for experts from EU and non-EU countries. It will be vital to reduce the high proportion of talents who return to other countries once they have completed their studies in Germany. According to the interviewees, the figure is as high as 90 percent in the Max Planck Society. Changing this situation will require the targeted **removal of the bureaucratic barriers** currently hampering visa applications, recognition of qualifications, granting of German citizenship and the establishment of companies by entrepreneurs from outside the EU.

As well as **funding a small number of elite research centres of excellence**, it is also necessary to **promote talent development more widely**. This need is indicated by the red arrows in Figure 10, which show that different kinds of robotics and AI specialists are required throughout the entire innovation process – from elite researchers with doctorates and post-doctoral qualifications, people with Master's degrees and application developers to people who can apply the technology in the field. The aim should be to train more talents across the entire spectrum of the robotics value chain, supported by measures to attract talents from abroad.

The **applied professions** are particularly important if Germany is to become a leading user. Improvements will be needed in the apprenticed occupations and at technical colleges and universities of cooperative education. At present, the training courses offered by these institutions do not adequately reflect the interdisciplinary nature of robotics. Dedicated curricula incorporating mechatronics, programming, process knowledge and the basics of robotics, AI and computer vision should be widely developed and made available on an extra-occupational and full-time basis.

5 Recommendations

This chapter proposes concrete measures based on the strategy outlined above and the suggestions of the interviewees.

5.1 Focus on becoming a leading user

Establish user-oriented robotopes with the aim of creating clusters to engage in the industrialisation and scaling of products from proof of concept to successful market rollout and in the co-creation of the regulatory framework. Robotopes are application consortia focused on a particular sector (for example manufacturing, intralogistics, agriculture, construction or healthcare) in which businesses (SMEs, large corporations) that are willing to industrialise robotics innovations collaborate with innovation providers (start-ups, researchers). The commercial risks are reduced through project funding and additional capital allowances.

The establishment of robotope networks can help to leverage synergies and foster a strong robotics ecosystem in Germany. As well as being key to the creation of a leading user market, this ecosystem could provide a focal point for the emergence of a globally competitive robotics OEM. It would also have a positive impact on elite research, talent acquisition, regulation and standardisation.

The **development of market-ready applications** in robotopes will call for the identification of **users with concrete automation requirements** followed by open calls for proposals for meeting these needs through project-based consortia. This will involve the following steps:

- Asking industry and other potential core users (in the construction, agriculture and service sectors) about their requirements;
- Determining the necessary funding instruments and required level of funding;
- Concurrent formulation of concrete implementation roadmaps;
- Calls for proposals from project-based consortia.

The first step is to **ask users about their requirements**. Project ideas for possible robotopes should be identified in collaboration with industry associations and their member companies, and the formation of the relevant **consortia** supported.

Once the requirements have been established, the users – who will be the main drivers of the robotopes – should identify the **funding instruments and level of funding** they will require to **implement** the relevant projects.

Once this has been established by the potential users, calls for proposals could be issued for appropriate project-based consortia of large enterprises, SMEs, start-ups, research institutions and universities. To ensure a highly **competitive** process, after the call for proposals for the robotope, several consortia would have to apply for the projects and relevant project funding.

This paper's proposals for strengthening the robotics ecosystem should be developed as soon as possible by a group of experts with access to the different user robotopes that also includes representatives of the German government. It will be necessary to define criteria for selecting users and their consortia and for following up the projects until their successful implementation in the market.

5.2 Talent acquisition

It is recommended that the ministries responsible for research and education should take the following measures in order to meet the extremely high and continuously **growing demand for qualified robotics and AI talents,** spanning everything from elite researchers and developers with Master's degrees to people who can apply the technology in the field:

- **Development and strengthening of robotics Master's programmes** at particular universities
  The chosen universities should be given the structural support to enable internationally competitive robotics teaching. Existing Master's programmes should be strengthened and new ones established, ensuring that the requirements of AI-based robotics are addressed (for example infrastructure-intensive teaching formats). As well as the latest research findings, teaching content should also cover practical applications and knowledge transfer and reflect the needs of industry. The aim should be to achieve excellence in robotics teaching so that even Master's graduates without a PhD can quickly start doing productive, specialised work in industry. The programmes should be advertised internationally in order to bring more foreign students with Bachelor's-level degrees to Germany.
- **Quality Pact for Robotics Teaching**
  Excellent robotics teaching that covers both theory and practical applications is infrastructure-intensive. The procurement, maintenance and preparation of complex robotics systems

for large numbers of students is beyond the means of most faculties. Teaching content must also reflect the needs of industry. The Quality Pact for Teaching that ended in 2020 is a non-subject-specific model which showed that quality and high student numbers are not mutually exclusive. A specific quality pact should be introduced for AI-based robotics teaching at universities and universities of applied sciences.

- **Strengthening the applied robotics professions**
  The applied professions are particularly important if Germany is to become a leading user. Robotics specialisms should be offered in the apprenticed occupations and specialist courses should be developed and expanded at technical colleges, vocational schools and universities of cooperative education. The focus should be on the interdisciplinary nature of robotics. In other words, as well as traditional subjects like mechatronics, the teaching content should also include robot programming, process knowledge and the basics of robotics, AI and computer vision. This should be available in the form of apprenticeships and on an extra-occupational and full-time basis. Funding should be provided to applicant schools and individuals (for example through the "Meister-BAföG" for people training to become a "master craftsman"). The training content should be determined in collaboration with the chambers of commerce and industry so that trainees receive a standardised vocational robotics qualification.

5.3 Elite research

- **Strategic innovation policy measures to strengthen robotics research excellence consortia**
  The interdisciplinary combination of robotics and AI plays to Germany's strengths in robot hardware, mechatronics and AI. As a result, there is still an opportunity to make the "Made in Germany" label a unique global mark of excellence that contributes significantly to the long-term competitiveness of Germany's market players.
  However, this will call for strategic innovation policy support for elite research that cannot be provided by the existing central and regional government instruments such as the *Excellence Strategy*, and that expands on the related concept of the *DFG Sonderforschungsbereiche* (special research areas). In this model, consortia apply for a long-term research project aimed mainly at establishing global leadership in basic research. The project is planned jointly by the consortium members, creates synergies and reduces overlaps. It should also contain strategic innovation elements that plausibly show how the research projects will help to meet the needs of the German actors in the value network and achieve ownership of the strategic control points, as well as generating prototypes that can be used in the relevant applications.
  One of the funded consortia should ultimately be developed into a German robotics competence centre along the same lines as the AI Competence Centre established in 2022. This measure should be supported by the establishment of a Graduate School of Robotics based on the Max Planck Schools concept. Max Planck Schools are a joint initiative of universities and non-university research organisations that allow young researchers to further their development within a strong research network. The new Graduate School for Robotics should be established in conjunction with one or more funded consortia and advertised internationally in order to bring more foreign talents with Master's-level degrees to Germany.
- **Improving teaching and research conditions in universities**
  The teaching load of German university professors is unusually high compared to other countries around the world. This often makes it difficult for German universities to recruit top foreign talents in the competitive global robotics and AI research environment. Meanwhile, the desired increase in robotics and AI student numbers also increases the organisational and mentoring workload. Accordingly, a resolution of the federal and state governments should be adopted to reduce the teaching load.

5.4 Regulatory framework and standardisation

- **Establishment of a multi-site interdisciplinary inspection and testing centre** for AI-based robots
  Innovative robot safety regulations that build on national and international norms, testing standards and certification expertise would provide a strategic control point and give German market players a concrete competitive advantage.
  It is necessary to develop inspection and testing procedures that allow robot manufacturers and systems integrators to verify that their systems are safe and provide certification bodies with the relevant tools. The model used could be similar to Euro NCAP, which defines, performs and assesses crash tests for the automotive industry using standardised, scientifically validated testing procedures. This would create a basis for guaranteeing occupational safety and for legal certainty and clarity regarding liability for AI-based robots placed on the market.

The AI dimension presents additional challenges such as ensuring safe machine learning, data security and data access rules and safe interaction. The regulations should be developed for stationary and mobile robots across all sectors. The strategic development of an effective international standardisation and certification body is therefore crucial. The establishment of a multi-site interdisciplinary research, inspection and testing centre for AI-based robots is also recommended. The centre should bring together research institutions, relevant industrial enterprises – especially technology leaders – and certification bodies. While the individual sites can specialise in certain technological aspects, industries, etc, they must all form part of a joint, coordinated, long-term strategic innovation project.

The project should specifically show how it will enable the German economic actors in the robotics sector to gain ownership of the control points in the value network and achieve long-term competitiveness. The concept of this centre is fundamentally different to that of regulatory sandboxes since its focus is on the creation of a permanent standardisation and certification capability rather than on the temporary extension of the regulatory framework.

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AI-based robotics is a key technology both for the realisation of Industrie 4.0 in manufacturing and logistics as well as for facing major social challenges such as demographic change. Technological breakthroughs are expanding the potential uses of robots outside of shielded industrial production cells: Thanks to an improved ability to recognise surroundings, as well as due to high-performing edge computing and advanced AI software, robots no longer just complete pre-defined tasks in structured environments – instead, they become intelligent systems which can navigate through unstructured, changing environments and complete complex tasks on their own or in cooperation with humans. Intuitive user interfaces and easy operation enable even laypersons to program robots, making robotics increasingly attractive for small and medium-sized enterprises. As a result AI-based robotics can help to improve life beyond industry application, for example in the areas of care, agriculture, construction and logistics.

This IMPULSE shows perspectives on how robotics can contribute to securing value creation in the face of intensifying global competition as well as to maintaining technological sovereignty and describes how Germany can become a leader in AI-based robotics, leveraging the country's existing industrial know-how in manufacturing technology and its internationally renowned research capabilities.