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COUNCIL FOR TECHNOLOGICAL
SOVEREIGNTY

Position Paper
Smart Robotics

Council for Technological Sovereignty

The Council for Technological Sovereignty

The „Council for Technological Sovereignty“ is an advisory body of the Federal Ministry of Education and Research (BMBF) and was convened in September 2021. It supports the ministry in identifying technology fields with longterm strategic importance. The council pools broad expertise from science and industry in key technologies and application fields.

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Technological sovereignty

Technological sovereignty is the ability to guarantee access to those key technologies that are necessary to implement societal priorities and needs at all times.

This includes the use and further development of technologies and products, taking into account available resources and necessary services, making gaps visible and closing them where possible, and helping to set standards in global markets.

Technological sovereignty may also require the independent development of key technologies and technology based innovations in Europe and the establishment of own production capacities within the value networks, if this is necessary to maintain the state‘s ability to act or to avoid unilateral dependencies, taking into account changing geopolitical boundary conditions.

This requires the ability to understand and evaluate all relevant technological development and manufacturing processes, and the ambition to work on an equal footing with strategic partners.

Background of the paper

The Federal Ministry of Education and Research has asked the Council for Technological Sovereignty to assess the field of smart robotics in the context of technological sovereignty. The background to this is an analysis by the Future Council of the Federal Chancellor (Zukunftsrat des Bundeskanzlers), that identified „AI-based“ robotics as an essential field with great potential and with high significance for Germany‘s resilience. The Future Council‘s analyses focused in particular on innovation potential and market development.

In this position paper, the Council for Technological Sovereignty examines the extent to which Germany is technologically sovereign in the field of smart robotics.

Executive Summary

Smart robotics is a technology-intensive field of application with high social and economic relevance. In the future, smart robots will be able to take on a wide range of different tasks – from parcel delivery by drone to mobile agricultural robots for cultivating fields, intelligent manufacturing robots in industry, or care robots for the elderly and the sick.

This position paper analyses the prerequisites and current status of technological sovereignty in smart robotics in Germany with regard to the availability of necessary key technologies and components, the combination of these components into complete systems and the availability of expertise in the form of skilled workers. The analyses show that Germany is able to compete internationally in the field of robotics, which applies in particular to „classic" robotics topics. Weaknesses can mostly be observed in areas strongly driven by developments and innovations in the field of artificial intelligence (AI) in robotics. In order to keep access to the „smart" aspects of robotics, this AI-driven technology field should receive a special political focus. The transfer into concrete applications should also be supported. Five policy measures are recommended:

- Maintaining and expanding Germany's relatively good international position in the field of robotics, with a particular focus on current trends in smart aspects of robotics through continued funding of cutting-edge research and operational applications.

- The promotion of application-oriented and interdisciplinary research and development projects in smart robotics in production and application, involving large industrial companies, SMEs and start-up companies in order to demonstrate the large application benefits of smart robotics.

- The expansion and facilitation of testing opportunities such as living labs and the promotion of vision-driven science communication on robotics.

- Supporting continuous education at all skill levels, including increasing the attractiveness of STEM subjects in general and promoting digital literacy.

- The introduction of a publicly available robotics monitoring to identify any risks and potentials of the field at an early stage.

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1. Smart Robotics

There are different approaches to the definition of a robot. Most established ones, e.g., ISO standard 8378 or VDI guideline 2860, have in common that the mechanism designated as a robot must be programmable and exhibit a certain degree of mobility and autonomy. The definition of the Japan Robot Association additionally distinguishes between different types of robots, depending on their flexibility, type of programming, or degree of autonomy.

According to the International Federation of Robotics (IFR), the number of industrial and service robots in commercial use worldwide was 4.3 million as of 2021. With around 3.5 million units, industrial robots make up the largest share, of which 5 % are in the German market, while China is by far the largest market with 52 %. For 2025, the IFR forecasts a global annual growth rate of 700,000 units per year for industrial robots. In its study „Industrial Robotics Market" (July 2022), the market research and strategy consulting company Emergent Research predicts a turnover of 120 billion US dollars for industrial robots alone in the year 2030.

This position paper focuses on smart robots. These robots are not only capable of performing a fixed task according to a static protocol, but also of reacting flexibly to external circumstances, autonomously recognising context and changing requirements, and adapting their actions accordingly. Smart robots do not include, for example, jointed-arm robots that carry out fixed and unchanging work steps in production, such as welding or screwing parts together, as autonomous action of the robot is not intended here. This is different with, for example, mobile autonomous assembly robots which use sensors such as cameras or LiDAR (light imaging, detection and ranging) to record their environment and can thus independently plan and implement work steps, such as locating and assembling components, even under changing conditions.

The options for using autonomously acting robots in various areas of application are expanding, fuelled by the rapidly increasing capabilities in the field of machine learning and artificial intelligence. Manufacturing work is just one example of the possible uses of smart robots. In agriculture they can autonomously water fields, fertilise, harvest or even recognise and treat sick plants. In the logistics sector, robots can not only sort and transport goods and consignments, but also deliver them directly to the customer, for example by drone. Robots are also already used in the domestic environment in the form of vacuuming and mopping robots, which increasingly act autonomously by using mapping functions to deal with highly changeable environments or to proactively avoid suddenly appearing obstacles. The use of robots in the immediate human environment extends furthermore to direct and interlocking cooperation between humans and robots in the form of socalled cobots. Another example of humanrobot interactions is movement support through active exoskeletons. In the future, an increasing number of robots working close to humans can be expected along with the improvement and refinement of robot capabilities and features. Even in challenging and heterogeneous environments such as individual medical care or home care, robots will more frequently take on tasks to support caregivers.

The versatile and complex application purposes and the corresponding requirements to robots' capabilities make smart robotics an application field in which a variety of key technologies are used (see chapter 2.2).

2. Technological Sovereignty in Smart Robotics: Survey

Since an increasing use of smart robots is to be expected in industry, everyday life, and many other areas, smart robotics has a high societal relevance. The Future Council of the Federal Chancellor has previously identified smart (AI-based) robotics as an essential field with great potential and high significance for Germany's resilience and has analysed its innovation potential and market development in particular.

Robotics and automation are also subject to increased focus by governments all over the world. The field is included in official lists of critical technologies or key technologies of Australia, the USA, the EU, France, China and Korea, among others.

In this paper, robotics is not treated as a key technology in its own right, but as a technology-intensive application field that combines and builds on various key technologies. Technological sovereignty in smart robotics is thus the ability to have access at all times to smart robots, as well as to the key technologies, knowledge and skills necessary to develop, produce and deploy smart robots.

A loss of technological sovereignty in the field of smart robotics entails the risk of losing room for manoeuvre in the development and use of robotics and thus falling into a de facto dependency in the manufacturing processes of a wide range of technologies, components, and products. Technological sovereignty is also a prerequisite for building up and sustainably securing export potential for the manufacturers of smart robots in Germany.

There is currently no central monitoring of developments in the field of smart robotics. This position paper is therefore based on our own analyses.

METHODS

The assessments presented in this paper are based on empirical indicators which reflect the subaspects of our definition of technological sovereignty. The indicators are derived from a **literature analysis**, a **patent analysis** and a **survey among experts**. Individual, topicspecific evaluations that were carried out in addition are not listed in detail here but are described in the corresponding text passages.

Scientific publications were examined with regard to the countries involved, new trends, and keywords used in the context of robotics. These reflect the area of basic research in particular and are a reliable indicator of existing expertise within the field of robotics.

In addition, **reports from various companies** in the robotics industry and from **analysts** were evaluated. In particular, trends in robot systems were identified that could be brought to market maturity in the foreseeable future and thus become useful for industry and society. The reports also allow a classification of the German and European start-up landscape in an international comparison.

Patent applications provide an indication of the innovation strength of a country's research institutions and companies. Therefore, both the countries involved, and the keywords used in current patents were analysed. In a top-down analysis, all patents filed in connection with robotic solutions were considered first. In addition, in a bottom-up approach, the focus was placed on smart robotics as such and analysed in detail. This involved filtering out those patents in robotics that had a clear focus on smart robotics.

Experts involved in the research and development of new robots have a clear picture of recent technological innovations in smart robotics. Therefore, **individual interviews** were conducted to better assess the global research and development landscape. These interviews served as a basis for classifying the results of the other analyses.

An **online survey among robotics experts** serves to validate the individual opinions on a broader basis. It contributes to a comprehensive picture of smart robotics in Germany and Europe in an international comparison.

2.1. Germany's Smart Robotics as Compared to International Standards

Germany is relatively well positioned in the field of robotics scientifically and economically, especially in more traditional fields such as control engineering, actuators and material innovations. In the last ten years, Germany has been among the five most successful countries worldwide in terms of both the number of high-ranking scientific publications and cross-legislative patent applications in the field of robotics. In a European comparison, Germany is clearly leading (cf. Figure 1 and Figure 2) .[i]

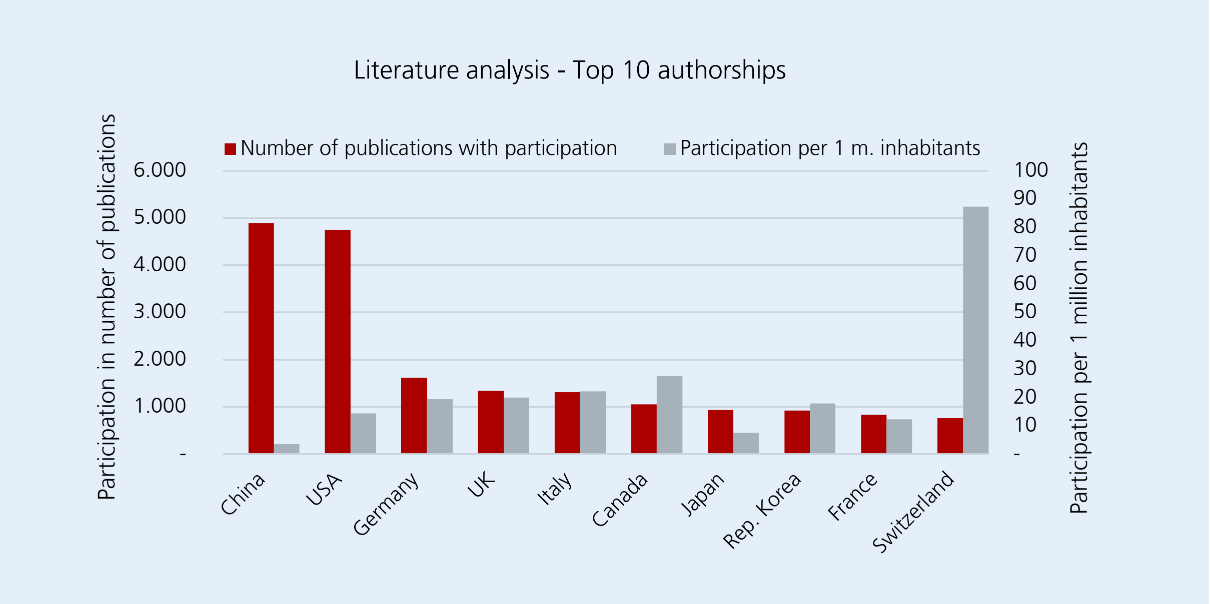

Figure 1 Number of high-ranking scientific publications of the top 10 countries with the most citations in the field of robotics and, for comparison, normalised to the population count. The publications are counted according to the participation of the respective country, as several countries are usually involved in a publication. (Sources: IEEE Xplore).

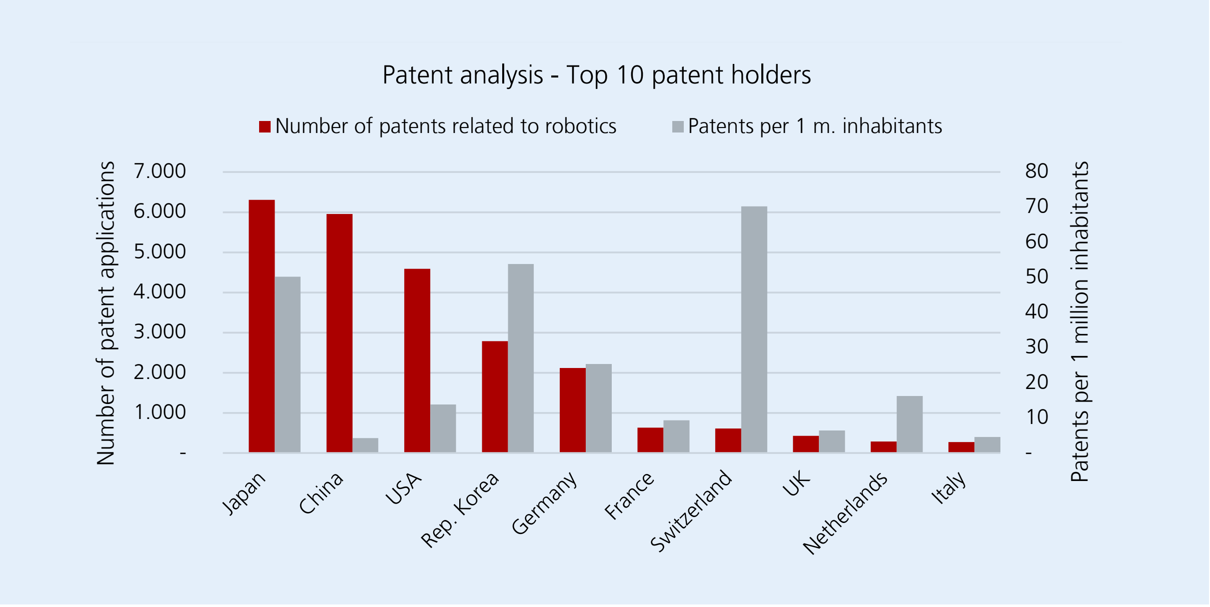

Figure 2 Number of cross-legislative patent applications in the respective top 10 countries in the field of robotics and, for comparison, normalised to the population count. (Sources: PatSnap, Eurostat).

A content analysis of patent applications in the field of robotics from the last ten years shows a strong focus: German expertise is concentrated in particular on topics related to the mechanics of robots, the „smart“ aspects of robotics such as artificial intelligence or communication technologies (cf. Figure 3) are less marked.

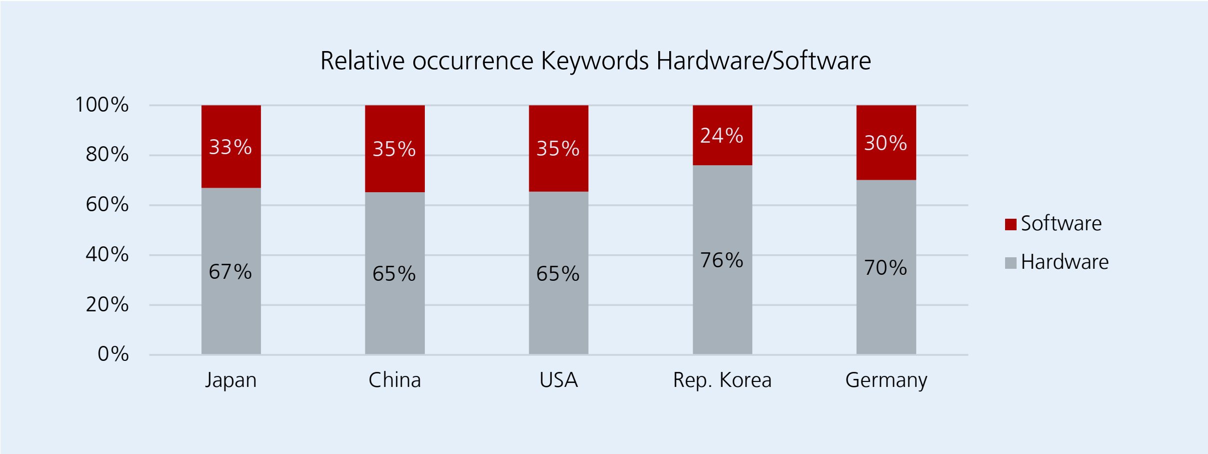

Figure 3: Relative occurrence of hardware/software-related keywords in patents (Source: PatSnap, own analyses)

Robotics-related companies based in Germany are mainly smaller and start-up companies. The start-up company „Agile Robots“ has been a unicorn since 2021. In terms of the total number of start-ups, Germany ranks at a similar level to England and France (see Figure 4). Most start-ups are founded in the USA, while experts also attribute very innovative start-ups to the Asian region, especially Japan.

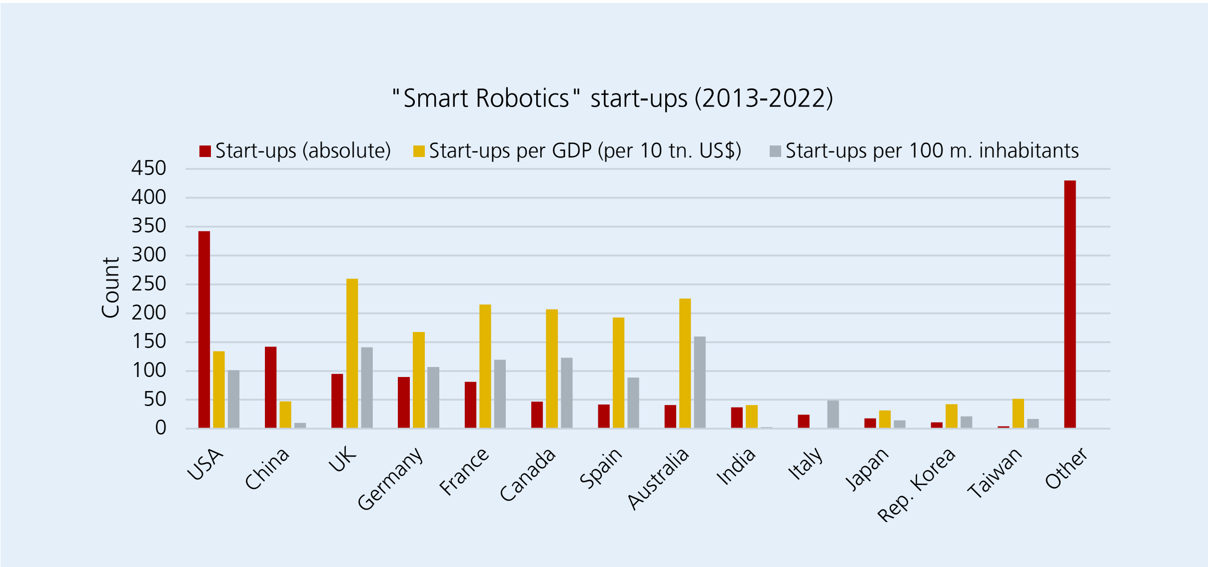

Figure 4: Illustration of the 13 countries with the most „smart robotics“ start-ups in the last ten years: Total number, by GDP and by population (Source: Startup database Dealroom.co).

2.2 Availability of key technologies and components

As a technology-intensive application field, smart robotics builds on the knowledge and availability of key technologies such as artificial intelligence, microelectronics, sensor technology and communication technologies. At the same time, robotics provides a basis for other fields of application, for example in industrial produc-tion. In order to be able to ensure technological sovereignty in smart robotics, all levels must be analysed - from the key technologies to their conjunction in the robot to the concrete application.

Hardware components form the basis of smart robotic systems. For example, the physical functions of a robot require drive elements, and especially robust, real-time capable and energy-efficient microelectronic circuits. To perceive its environment, a robot also needs sensors, which can be optical, magnetic, acceleration or temperature sensors.

Network and communication structures play a major role in coordinating smart robots in and with the system in which they operate. Furthermore, they enable an efficient distribution of computing power, for example to perform computationally intensive tasks such as simulations and analyses. In the context of 6G mobile research, smart robotics (CoBots and networked robots) is a central field of application.

The need for software in smart robotics ranges from direct control of the hardware via operating systems and drivers to analysis and AI software for processing sensor data for smart decision-making and its translation into the robot's actions. Robots must be able to communicate with each other and, if necessary, with the system in which they are integrated, to exchange (learned) information. Computing power must be distributed intelligently, digital twins of environments or objects support safe interaction by simulating processes. Close integration of sensor technology and data processing is therefore essential for the development of smart robots.

The analyses (including a survey among robotics experts, see Figure 5) show weaknesses in Germany compared to non-European countries, especially the USA, in the field of artificial intelligence. Robotics places special de-mands on AI methods that can differ from the currently discussed demands on AI methods in other areas. In robotics, AI is used in many different areas with various requirements, such as image segmentation and recog-nition, analysis of depth maps and 3D models, recognition of human intentions based on movements or facial expressions and, in general, the content analysis and combination of sensor data of all kinds.

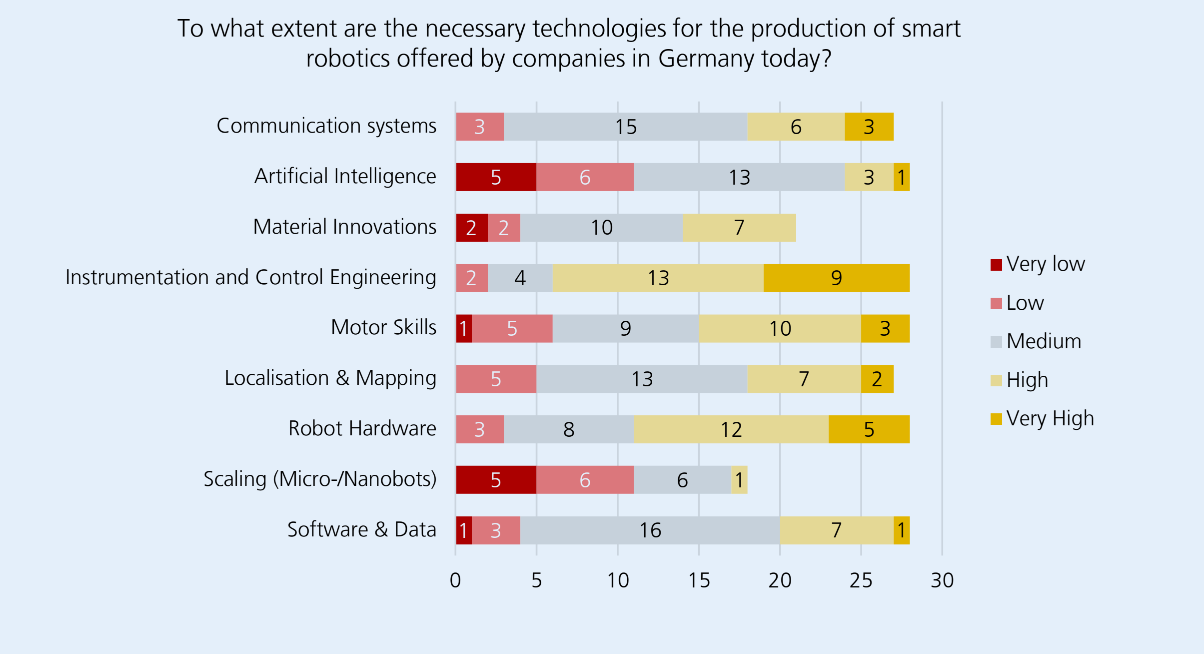

Figure 5: Answers by robotics experts to the question about the availability of various technologies in Germany. (Source: own survey; n=31).

A number of federal and state programmes exist to strengthen AI research in Germany, for example the crea-tion of 100 new professorships as part of the Federal Government's 2018 „Artificial Intelligence Strategy", which at the same time addresses the shortage of teaching staff across all levels of education (see chapter 2.4). At 14% , a significant proportion of these professorships in AI are focused on the field of robotics.

2.3 Combination into Complete Systems: Integration and Interdisciplinarity

The availability and advancement of the underlying key technologies is a necessary but not sufficient condition for technological sovereignty in smart robotics. Robotics-specific concepts, software, components as well as know-how in research, development and application are imperative so that different basic and key technolo-gies can be combined into smart robots.

In addition, suitable interfaces between the individual components are needed. There is competitive produc-tion in Germany – nevertheless, the focus on integrating these individual components into complete robotic systems can be expanded. Particularly when analysing patents, it is noticeable that comparatively few of the German applications relate to complete systems. Here, Germany ranks behind other countries with a similar number or more patent applications, especially the USA and Korea.

With the increasing spread of smart robots in the immediate environment of humans - in the home, in traffic, in industry (cobots), medicine and care - the need for expertise on the human-machine interface and interac-tion is also increasing, especially apropos of end users who are not trained in the use of robots. In order for this interaction to take place in a controlled and reliable manner at all levels, ethical, social and psychological con-texts must be considered at an early stage in addition to technical issues. Robots must act in a comprehensible and controllable way so that both the perceived and the actual safety in the human-robot interaction is en-sured (Function Safety and Conformance). The participation of psychologists, sociologists and philosophers in robotics research is comparatively low in Germany. A corresponding analysis of the specialist literature has shown that the USA, China and the UK have a clear lead here.

A safe use of robots also requires extensive testing, especially under realistic conditions. Test facilities for smart robots do exist in Germany - for example, there are two recently opened test areas for underwater robots (off Helgoland in 2019 and off Nienhagen in 2021) - but their usage is overcomplicated by bureaucratic hurdles. Restrictive conditions of use, security measures and lengthy as well as complicated administrative steps discour-age small companies in particular from using test facilities and living labs. In practice, many robotics research teams therefore conduct tests in other European countries. Another hurdle are legal restrictions on testing procedures, especially concerning medical robots.

The Federal Ministry for Economic Affairs and Climate Protection is currently drafting a bill on regulatory sand-boxes. The published concept envisages, among other things, facilitating access to testing opportunities in Germany by establishing „one-stop shops", especially for small and medium-sized enterprises (SMEs) and re-search groups without adequate legal capacities. Experimentation clauses are intended to create exceptions in new and existing laws that legally facilitate the testing of new developments.

Due to the versatility of robots, concrete use cases are often very specific. The integration in companies there-fore often requires a lot of time and expenses and is seen as disproportionate to the expected benefits. Currently, system integrators are needed to bring smart robots into application, for example by integrating a robot into the production process at the appropriate point. However, recent trends are moving towards bypassing this expensive solution by designing smart robots to be easy to integrate. This makes it possible to implement them in different types of processes, which in the best case can also be carried out by laypersons without any special training regarding the operation of such a robot. In the future, system integrators might only be need-ed for initial implementation.

2.4 Shortage of Skilled Workers

In addition to the required technologies, skilled workers with the corresponding expertise for hardware, soft-ware, and processes must be available. The development, production, operation, and maintenance of systems and solutions with smart robots are different tasks, for each of which specialist expertise is needed.

The current shortage of skilled workers poses a risk to technological sovereignty. A survey among robotics experts has shown that the issue varies in severity depending on the level and focus of training. The shortage of skilled workers in application-oriented occupations in the field of smart robotics is considered to be even greater than the shortage of university graduates.

As a research location for robotics-related disciplines, Germany is moderately attractive for top researchers (top 2 percent by h-index), as can be seen from an analysis of the Stanford list of the most successful scientists (see Figure 6). As the third most represented country on the list, Germany is ahead of all other European countries and has a similar proportion of extraordinarily successful scientists (by h-index).

There is also a need for action when it comes to training and further education on the subject of intelli-gent robotics in companies.This applies in particular to the goal of bringing smart robots into large-scale application. High amortisation periods and unclear business models are currently still preventing the widespread use of smart robots.

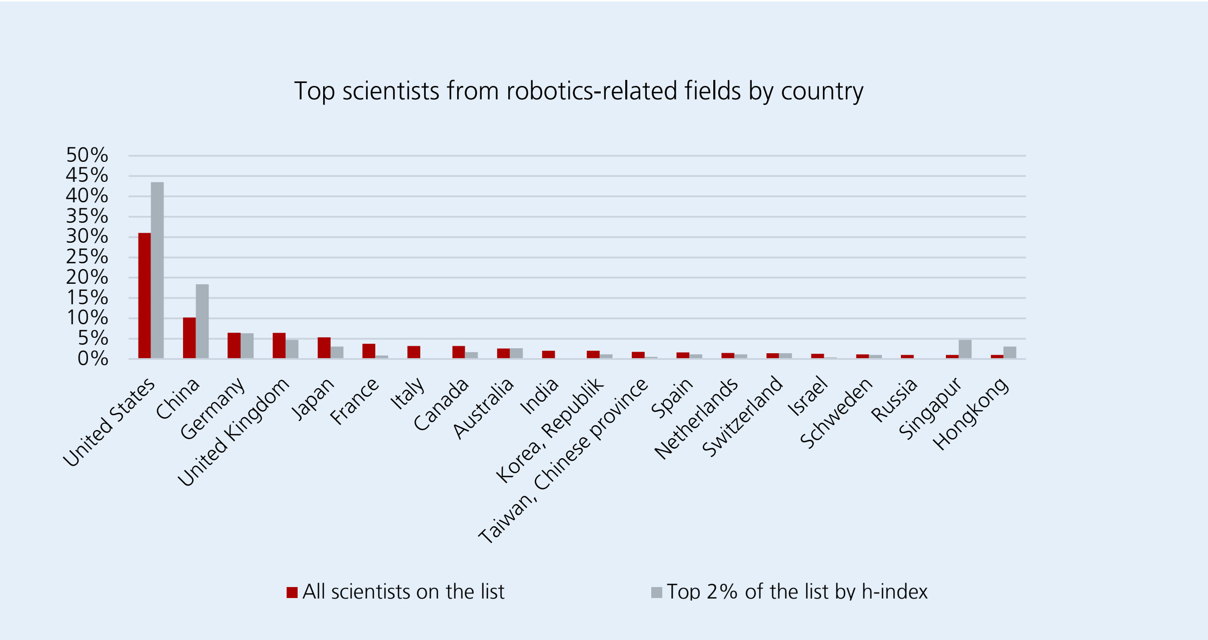

Figure 6: Illustration of the 20 countries with the most researchers in the field of smart robotics, according to percent-age share. In addition, the distribution of the scientists who are most successful according to the h-index (average number of citations per publication) is shown. (Source: Baas, Jeroen; Boyack, Kevin; Ioannidis, John P.A. (2021), „Au-gust 2021 data-update for „Updated science-wide author databases of standardised citation indicators““)

Overall, the comparatively low level of digital skills in Germany across all levels of education is a structural prob-lem that concerns not only smart robotics. There is an urgent need to catch up in this regard (cf. Figure 7).

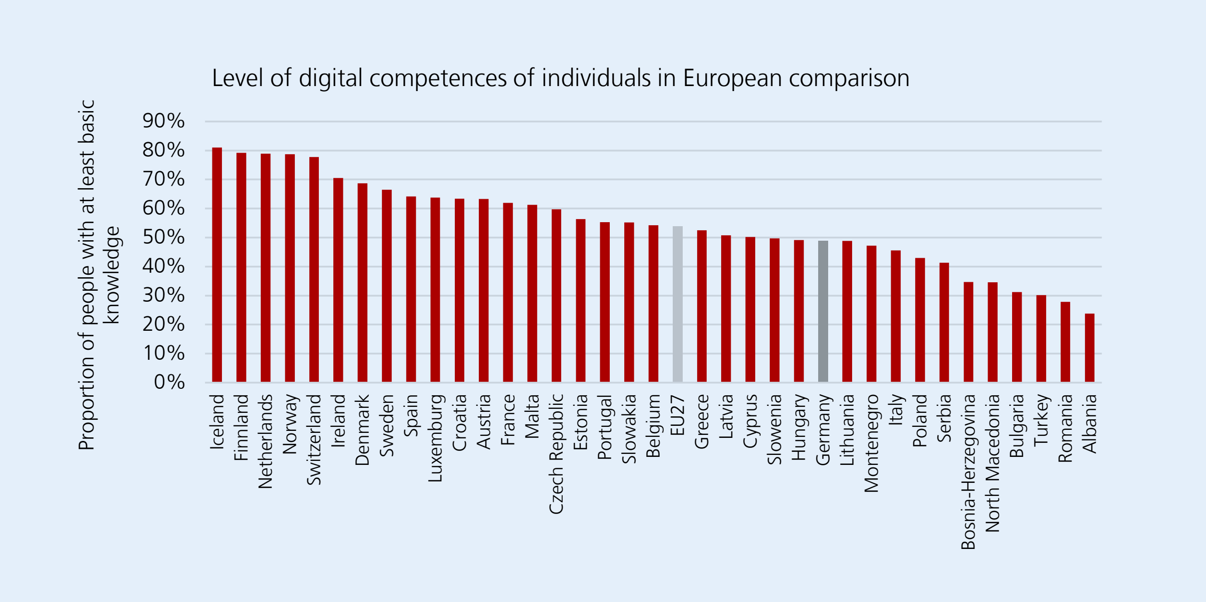

Figure 7: Level of digital literacy of individuals in Europe: share of individuals with overall basic or higher than basic digital skills - 2021 (Source: Eurostat)

3. Recommendations for Action

Germany is currently well positioned in robotics, especially in more traditional fields such as control engineering, actuators and material innovations. This good international position should be maintained. With regard to current trends towards more smart and autonomous robotics solutions, a comparatively low focus on artificial intelligence and smart aspects of robotics can be observed in Germany. In order to ensure technological sovereignty in robotics in the future, special focus should be assigned to these aspects.

In summary, we recommend the following measures in the context of Germany's technological sovereignty in the field of smart robotics:

- Maintaining and expanding Germany's relatively good international position in the field of robotics, with a particular focus on current trends in smart aspects of robotics through continued funding of cutting-edge research and operational applications.
- The promotion of application-oriented and interdisciplinary research and development projects in smart robotics in production and application, involving large industrial companies, SMEs and start-up companies in order to demonstrate the large application benefits of smart robotics.
- The expansion and facilitation of the use of testing opportunities such as living labs and the promotion of visiondriven science communication on the topic of robotics.
- Supporting continuous education at all skill levels, including increasing the attractiveness of STEM subjects in general and promoting digital literacy.
- The introduction of a publicly available robotics monitoring to identify any risks and potentials of the field at an early stage.

Focus on market-relevant applications of smart robotics

In Germany, expertise in systems engineering, i.e., the combination of components to form complete systems, is definitely present. However, competences to integrate smart robots productively on the user side are less pronounced. To facilitate this integration, the technical competence for concrete implementation should be supported on the side of the industrial users, for example through the establishment of transfer centres. With the trend towards greater focus on AI and information and communication technologies in robotics, an increasing importance of standardisation in exchange with international partners is to be expected and should therefore be addressed. International cooperation, especially in research, is a fundamental prerequisite for the successful development of new robotic innovations.

Interdisciplinary research from a user perspective

The integration of robots should be approached with the application in mind: Application scenarios and demands should be consistently considered throughout the development process. This also requires increased promotion of interdisciplinary approaches in research projects. Different disciplines and concrete aspects of use should be considered, and industrial stakeholders should be involved. Ethical and psychological aspects should, where appropriate, be integrated into the development process from the outset, in order to create optimal conditions for socially acceptable and functional robotics solutions and products.

Promotion and simplification of tests under real conditions

In the case of test opportunities for new robotic developments, more intensive support and relief for researchers is necessary, e.g., through comprehensive guidance and assistance in the use of test fields and living labs. The respective regulatory conditions should be simplified and restrictions reduced, for example through experimentation clauses. Living labs and positively communicated concrete application scenarios for smart robots also offer the potential to increase the visibility of new robotic innovations and to positively shape their social image, as well as to create an environment for continuous education in this field.

Increasing the attractiveness of the field for skilled workers and strengthening competences

Such an environment also counteracts the shortage of skilled workers and thus helps to maintain Germany's international competitiveness. In order to enable the actual implementation of robotics solutions in marketable applications, users need to have competence in evaluation. This should be strengthened through training offers at all qualification levels, especially for companies that cannot provide these trainings themselves. A central mean here should be to increase the attractiveness of STEM subjects, starting in early childhood education and continuing throughout all levels of education. The same applies to the general digital skills of potential robotics users, which should be improved across all age groups and educational levels - with a particular focus on older people and non-academic professions - to catch up internationally in these areas.

Introduction of robotics monitoring to identify any risks and potentials

Possible risks and potentials of smart robotics should be made visible with a longterm and publicly accessible monitoring specifically tailored to this field. The main focus should be the early identification of unilateral dependencies, considering geopolitical and geo-economic aspects. The availability of raw materials should also be covered as a fundamental prerequisite for technological sovereignty, for example by means of import flow analyses. On the economic side, venture capital and start-ups should be monitored. International research cooperation and the participation of German representatives in international standardisation committees should be continuously recorded. It is conceivable to integrate the monitoring of smart robotics into an already existing technology radar, provided this is compatible with its public availability.

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[i] For the evaluation of scientific publications, the quality criterion of the number of citations was used (the 2,000 most frequently cited publications per year); for patents, the quality criterion of breadth of market by patent families was used (patents with applications in at least two different jurisdictions based on the socalled patent families, so that the evaluation criteria of at least two jurisdictions must be fulfilled and thus multiple evaluation of the same patents with identical content is avoided).

[ii] Source: https://www.bitkom.org/ki/forschung

[iii] Source: https://www.bmwk.de/Redaktion/DE/Publikationen/Digitale-Welt/konzept-fur-ein-reallabore-gesetz.pdf?__blob=publicationFile&v=4

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