ISSN 1831-9424

European Commission

JRC TECHNICAL REPORTS

AI Watch
AI for enhancing Robotics

The intersection of Robotics with the AI Landscape

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EUR 31198 EN

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JRC128846

EUR 31198 EN

PDF ISBN 978-92-76-56388-4 ISSN 1831-9424 doi:10.2760/314545 KJ-NA-31-198-EN-N

Luxembourg: Publications Office of the European Union, 2022

How to cite this report: Righi, R., Papazoglou, M., Samoili, S., Vazquez-Prada Baillet, M., Cardona, M., Lopez Cobo, M., De Prato, G. and Duch Brown, N., *AI Watch: AI for enhancing Robotics, The intersection of Robotics with the AI landscape*, Publications Office of the European Union, Luxembourg, 2022, doi:10.2760/314545, JRC128846.

Contents

Abstract

This report provides insights on the composition and status of Artificial Intelligence for enhancing robotics around the world, with a specific focus on the European Union. AI for enhancing robotics is understood in this report as the intersection between artificial intelligence and robotics and is identified by exploring the presence of activities related to robotics within the global AI landscape. The AI for enhancing robotics domain is mapped and explored in three subdomains and several thematic areas by employing the JRC Techno-Economic Segment approach. Based on a tech-mining approach, we look at the players (firms, research institutes and governmental institutions) active in AI for enhancing robotics internationally. Furthermore, we describe players that produce or commercialise products and services related to AI for enhancing robotics. After conducting a bottom-to-top exercise, we identify three subdomains. In decreasing order of closeness to market these are: (i) “AI for enhancing Robotics Industry”, (ii) “AI technological support for Robotics”, and (iii) “AI for enhancing Robotics Research & Innovation: Publications and Projects”. We also observe how the presence of ancillary B2B services integrating AI for enhancing robots in existing economic activities is emerging. The report’s findings confirm that the US, China and EU27 are the leading players in the AI for enhancing robotics landscape, in a supply perspective. The EU27 shows an important specialisation in most of the thematic areas. Considering EU Member States (MSs) individually, the highest numbers of players are concentrated in Germany, France, Spain and Italy.

Keywords

Artificial Intelligence, Robotics, techno-economic landscape

Foreword

This report is published in the context of AI Watch, the European Commission knowledge service to monitor the development, uptake and impact of Artificial Intelligence (AI) for Europe, launched in December 2018.

AI has become an area of strategic importance with potential to be a key driver of economic development. AI also has a wide range of potential social implications. As part of its Digital Single Market Strategy, the European Commission put forward in April 2018 a European strategy on AI in its Communication "Artificial Intelligence for Europe". The aims of the European AI strategy announced in the communication are:

- To boost the EU's technological and industrial capacity and AI uptake across the economy, both by the private and public sectors
- To prepare for socio-economic changes brought about by AI
- To ensure an appropriate ethical and legal framework.

Subsequently, in December 2018, the European Commission and the Member States published a "Coordinated Plan on Artificial Intelligence", on the development of AI in the EU. The Coordinated Plan mentions the role of AI Watch to monitor its implementation.

Furthermore, in April 2021 the European Commission proposed a set of actions to boost excellence in AI, and rules to ensure that the technology is trustworthy. The proposed Regulation on a European Approach for Artificial Intelligence and the update of the Coordinated Plan on AI aim to guarantee the safety and fundamental rights of people and businesses, while strengthening investment and innovation across EU countries. The 2021 review of the Coordinated Plan on AI refers to AI Watch reports and confirms the role of AI Watch to support implementation and monitoring of the Coordinated Plan.

AI Watch monitors European Union's industrial, technological and research capacity in AI; AI-related policy initiatives in the Member States; uptake and technical developments of AI; and AI impact. AI Watch has a European focus within the global landscape. In the context of AI Watch, the Commission works in coordination with Member States. AI Watch results and analyses are published on the AI Watch Portal (https://ec.europa.eu/knowledge4policy/ai-watch_en).

From AI Watch in-depth analyses we will be able to understand better European Union's areas of strength and areas where investment is needed. AI Watch will provide an independent assessment of the impacts and benefits of AI on growth, jobs, education, and society.

AI Watch is developed by the Joint Research Centre (JRC) of the European Commission in collaboration with the Directorate-General for Communications Networks, Content and Technology (DG CNECT). This report addresses the objective of AI Watch of mapping and monitoring the worldwide landscape of AI, in particular by providing insights on the composition and status of the intersection between AI and Robotics as seen through the AI worldwide landscape, with a specific focus on the EU landscape.

Acknowledgements

The authors would like to thank Filipe Jones Mourao (DG CNECT) for his comments and the interaction on earlier drafts of this report. Similarly, we thank other colleagues from DG CNECT participating in meetings to discuss early findings and labelling of emerging subdomains and thematic areas. We also acknowledge the collaboration of several colleagues from AI Watch, in particular Paul Desruelle, Josep Soler Garrido, Eva Martínez Rodríguez and Emilia Gómez.

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1 Introduction

In recent years the rapid increase of processing power and data availability combined with improved algorithms and new methods has led to achieve significant technological accomplishments in the field of Artificial Intelligence (AI) (Zhang et al., 2021). Great efforts have been made to building intelligent systems that can perform tasks, either without human intervention or alongside humans, which could enhance social living standards and individual quality of life, and to improve the capacity and efficiency of economic production, but has also raised questions on working conditions and employment. New technologies, mainly related to AI and the Internet of Things (IoT), have triggered what is considered by some to be the "Fourth Industrial Revolution" (Schwab, 2017). In view of these developments, AI has become an area of strategic importance, as underlined in the European strategy on AI (European Commission, 2018a) and in the related Coordinated Plan (European Commission, 2018b, 2021). The European Commission (EC) has impacted on the whole AI lifecycle by, for example, promoting basic and applied research and development; setting up industrial partnerships; incentivizing innovative start-ups and regulatory sandboxes; and considering implications related to safety and liability (European Commission, 2021).

In parallel with analysing the increasing pervasiveness of AI across sectors (Emmert-Streib, 2021), many studies have provided evidence on the implications and impact of robotics on several fields. Luciano, Luciano, Gabbert, and Seshadri-Kreaden (2016) investigated the role of robotics on the medical sector. They concluded that robotics has been successfully integrated without compromising patient outcomes or changing the overall approaches. Qureshi and Syed (2014) meanwhile explored the impact of robotics on employment and motivation of employees in healthcare. Dirican (2015) has discussed the future of robots, mechatronics and artificial intelligence on business and economics, while Pham, Madhavan, Righetti, Smart and Chatila (2018) focused on issues in the field of social robotics, social care and the social professions in terms of challenges, ethics, human-robot relationships and acceptance.

While robotics implementations are expected to increase in the manufacturing sector, new applications targeting a variety of fields may be found, from ageing, to health, transport, security, energy and the environment (European Commission, 2020). Back in 2013, Neelie Kroes (who was then the EU Commissioner for the Digital Agenda) launched the partnership stating that "this is a great opportunity for Europe. These PPPs will maintain our global lead in robotics […] Combined with a comprehensive industrial strategy, the PPPs will ensure vigorous European leadership and a better future for all" (Kroes, 2013). In 2015, the EC launched the SPARC public-private-partnership on robotics [PPP] with euRobotics AISBL. With a budget of € 700 million (SPARC, 2015) this sought to promote research, job creation and innovation through better and safer robots. More recently, in 2021 the PPP was merged with others to create a single and bigger partnership addressing robotics, AI and data (Adra, the "AI Data Robotics Partnership" ([1]) which is one of the European Partnerships in digital, industry and space in Horizon Europe). The private sector side of Adra is composed of BDVA, CLAIRE, ELLIS, EurAI and euRobotics. The expected investment plan foresees € 1.3 billion to be invested by the EC, matched by private funding to achieve € 2.6 billion by 2030.

In the same direction, the consistent attention of the FP7 policy cycle was directed to research related to the "perception, understanding, action-cognitive, and intelligent enabling technologies" (IFR, 2021c). More recently, new objectives have been established regarding the "digital transition of the manufacturing and construction sectors, autonomous solutions to support workers, enhanced cognition, and human-robot collaboration based on research into digitisation, AI, data sharing, advanced robotics, and modularity" (IFR, 2021c). In addition, it is stated in the recent Review of the Coordinated Action Plan on AI that "Robotics powered by AI is a key enabler for the EU's productivity, competitiveness, resilience, and open strategic autonomy while preserving an open economy in the digitalising world" (European Commission, 2021). At the occasion of the JRC International Conference on Robotics in 2021 ([2]) Commissioner for Innovation, Research, Culture, Education and Youth, Mariya Gabriel, stressed the expectation that robots would "help our societies in achieving successfully the digital and green transitions", and would have "a concrete and direct impact on the daily lives of all the citizens". In a similar vein, the Vice-President for Inter-institutional Relations and Foresight, Maroš Šefčovič, reminded us that Europe has been leading global R&D on robotics and AI, and that Robotics could make the EU's industry more competitive and sustainable.

In view of such expectations, it is important to take a close look at what we call robots and which evolutionary paths robotics could possibly take. Above all, the implementation of larger degrees of "intelligence" appears to

([1]) https://ai-data-robotics-partnership.eu/

([2]) "What future for European robotics? A science for policy perspective", from January 27 to 29, 2021 (retrieved on July 15, 2021 at https://knowledge4policy.ec.europa.eu/news/what-future-european-robotics_en) be a game-changer, as it allows robots to operate without any human intelligence control or supervision. Robots can currently also operate based on telecommunication tools which allow a remotely located operator to have full control (e.g., bomb-disposal robots). Clearly, the major limitation of such devices is that the intelligence is external and not incorporated in the machine itself, and thus the presence of an operator is still required. The latest technological developments related to computational power, algorithmic improvements, and machines' operational interconnectivity have boosted the take-off of AI (Righi et al. 2021). This, in turn, is expected to bring many opportunities for robotic applications. Indeed, AI will reduce the dependency of robots on the presence of operators, and it will allow robots to handle different types of available information for adjusting their activities and making their working process more efficient. Therefore, robotics is a domain in which the integration of AI opens up new opportunities for expansion, with important implications in industry, health care, transport and logistics, customer services, and home maintenance, among others (Samoili et al., 2020). The present report aims to shed some light on the application of AI to robotics, exploring in detail robotics' AI landscape.

Scope of the Report

The present work sets out to address the part of the robotics domain which implements AI, and which we refer to as AI for enhancing robotics (AIeR). Robots that are not supported by AI are therefore not considered in this study. The two main categories of the overall "robotic" domain are industrial robots and service robots. The former are typically meant to be programmed for very specific types of applications and are employed to carry out repetitive tasks. They are limited to a set of actions they are designed to operate, and they must be re-programmed if this set of operations changes. Service robots are developed to (i) operate in a relatively complex environment with other machines and potentially also interact with humans, and (ii) perform multiple operations without any prior exact set of instructions or programmed sequence of actions. Despite the versatility of the latter category, robots of this kind are not able to learn and adapt their own functions based on parameters regarding the contexts in which the activity is performed.

The implementation of AI allows advanced robots to have a higher degree of autonomy and self-adaptability, which allows them to be employed in complex contexts where human-machine interaction is foreseen. More specifically, while for industrial robots the application of AI is related mainly to the adaptability of machines' operations based on some exogenous parameters (i.e., related to the working contexts and the production process flow), AI allows service robots to achieve one specific goal (or more) with no prior, exact, and detailed definition of the sequence of actions to be implemented. So, in both cases, robots gain in operational flexibility by using AI.

This report offers an overview of the economic landscape of AI for enhancing robotics, by monitoring international industrial and research activities from 2009 to 2020. Based on tech-mining techniques (Porter et al., 2004), we first identify the economic players (firms, research institutes and governmental institutions) that are active in the field. The main research questions are about providing: (i) the identification of subdomains and thematic areas within the AI for enhancing robotics domain to disentangle its content and detect different areas of intersection between AI and Robotics; (ii) an overview of the global situation; and (iii) a deeper exploration of the EU27 landscape.

To our knowledge, no information specifically addressing the development, production, and commercialisation of AI for enhancing robotics is currently available.([3]) Other studies on the domain mainly report statistics and other information on the adoption of robots worldwide or refer to specific economic sectors (most of these works are developed with information collected by the International Federation of Robotics, IFR). The present work instead adopts a "supply-side" perspective, in the sense that it targets the economic players providing and, therefore, enabling the use and diffusion of this technology. Hence, this report complements the existing studies and information about the application of AI in the robotics domain.

In addition, instead of exclusively using the top-down ISO product-based standard classification ([4]) as its baseline, this study considers such classification together with a bottom-up analysis on economic activities. Collected information includes for example firms' core-business activities, patents, publications and, when considering EU Member States, EU-funded projects. On the one hand, this allows us to identify emerging subdomains and thematic areas in a technological domain/field which is completely new and that therefore

([3]) In the framework of the AI Watch, the report "Evolution of the EU market share of robotics: Data and methodology" (https://knowledge4policy.ec.europa.eu/publication/evolution-eu-market-share-robotics-data-methodology_en) provides a review of the robotics industry.

([4]) ISO 8373:2012; https://www.iso.org/obp/ui/#iso:std:iso:8373:ed-2:v1:en cannot be fully captured by current standards, i.e., ISO classification. On the other, the match with the standard ISO classification is considered and discussed to allow comparison and consistency. This approach allows us to have a more accurate picture of the intertwining of different technologies and an updated view of the technological similarities characterising activities in this new domain, even if the resulting characterisation may identify areas referring to more than one product-base category.

The structure of this report is as follows. Section 2 introduces the approach; Section 3 gives an overview of the worldwide AI for enhancing robotics landscape, focusing on the presence of AI for enhancing robotics in countries and investigates the degree of specialisation for the main global players within each AI thematic area, analysing country profiles and identifying thematic hotspots; Section 4 provides a detailed picture of AI for enhancing robotics in the EU27 at country level; and Section 5 concludes.

2 Identifying the AI for enhancing robotics landscape

2.1 Background and methodology

To investigate the AI for enhancing robotics landscape, we build our own unique dataset by applying to the AI domain the Techno-Economic Segments (TES) approach developed by the EC Joint Research Centre (JRC). This section presents a summary of the methodological steps and focuses on the additional elaborations introduced for this specific work.

Starting point is the JRC TES analysis from 2020 (Samoili et al., 2020; Righi et al., 2020), which maps the AI worldwide landscape by considering the main AI-related industrial, innovation and research activities, and the economic players that are involved in them (i.e., firms, research institutes and governmental institutions). Relying on multiple data-sources aimed at covering different aspects of the considered techno-economic landscape, micro-data are retrieved in order to detect the identity and location of the economic players involved (firms, universities, research institutes, local government institutions), and their involvement with respect to AI. By means of tech-mining techniques, mainly relying on the initial selection of technology-related keywords, an initial set of queries allows the identification of documents describing different types of activities related to AI. Through the consideration of multiple data sources, we collect information about (i) industrial activities (i.e., firms whose core-business is AI); (ii) research activities (i.e., scientific publications on AI); and (iii) innovation activities (including patent applications ([5]) and European R&D Projects ([6])). The data sources considered to collect information are: (i) Crunchbase, DowJones, and Orbis for industrial activities; (ii) Microsoft Academic Graph (MAG) for scientific publications; (iii) FP7 and H2020 data for EU R&D Projects; and (iv) Patstat to cover innovation activities. For any detected document, the involved players are identified and the structure of collaborations is kept, and the final data is structured in form of a network. This is how TES provides an interconnected view of the worldwide AI ecosystem from 2009 to 2020.

The initial tech-mining process identified the players (firms, research institutes and governmental institutions) that are actively involved in AI over the considered period (2009–2020). By doing so, the approach can identify players who are producing and commercialising AI-related products and services (i.e., AI-related industrial activities), as well as to identify the players that are actively contributing to the development and progress of the technology (i.e., by means of AI-related scientific publications and AI-related patents). Finally, it provides information on the location of players and the relationships that – in some cases –the players develop, and this allows us to characterise a geographical "landscape" of relevant players.

To disentangle the complexity of the entire worldwide AI landscape, nine AI thematic areas have been identified by means of a bottom-up analysis. The textual content present in the description of any detected activity (e.g., abstract, title and main body in scientific publications) has been processed by an unsupervised algorithm based on topic modelling allowing the identification of thematic areas within the domain considered, i.e., AI (Samoili et al., 2020; Righi et al., 2020, 2021). These are: (i) "audio and natural language processing" (NLP); (ii) "computer vision applications"; (iii) "machine learning (ML) fundamentals"; (iv) "machine learning (ML) for image processing"; (v) the "internet of everything (IoE)"; ([7]) (vi) "automation"; ([8]) (vii) "autonomous robotics"; ([9]) (viii) "Connected and Automated Vehicles" (CAVs); and (ix) "AI services" (Righi et al., 2021).

From a methodological point of view, to address the AI for enhancing robotics (AIeR) landscape, we consider the "autonomous robotics" thematic area that emerged from the AI landscape as the baseline. Nonetheless, as the complexity of the landscape lies in the intertwining of the different AI thematic areas, we cannot exclude that

([5]) The EPO Patstat database offers a worldwide coverage of priority patent application filings.

([6]) In this case, FP7 and Horizon 2020 projects have been considered. To avoid a bias with respect to the worldwide landscape, we consider information related to the European R&D projects only when monitoring EU Member State performance.

([7]) IoE: Activities referring to the interconnectivity of various technologies, processes and people. The human interaction in this context allows people to monitor or configure devices and processes through interfaces.

([8]) Automation: Activities related to the production or use of physical machines, computer software and other technologies to perform repetitive tasks, for which they are specifically designed and programmed. They can have several degrees of freedom, e.g., in terms of movement. They may include intelligent control modules to interact with the environment in a controlled setting, e.g., using a temperature sensor. However, they are limited to a set of actions for which they are designed to operate, and have to be re-programmed for new or additional operations. The use of AI in automated machines is mainly related to the adaptation of the defined set of operations as a reaction to external parameters.

([9]) autonomous robotics: Activities related to the development or use of robotic systems that are meant to operate in a relatively complex environment involving interaction with other machines or humans. Autonomous robots perform multiple operations without any prior exact set of instructions, nor programmed sequence of actions. AI allows autonomous robots to have this higher degree of autonomy when compared to automated machines.

the players mainly active in other AI thematic areas can also have a role in this domain. Therefore, the presence of AI for enhancing robotics within the remaining thematic areas of the whole AI landscape has been considered as well. In this sense we investigate each of the eight remaining thematic areas of AI to verify whether there are thematic subparts related to AIeR. This procedure has been performed with the same topic modelling technique implemented for the investigation of the thematic areas in AI (Samoili et al., 2020; Righi et al., 2020; 2021). However, while in the investigation of the AI landscape the objective was to unveil the thematic areas that are emerging and understand their properties, here the objective is to detect the presence of certain "robotics-related" activities. This further topic modelling analysis (on one AI thematic area at a time), is performed with the aim of exclusively detecting groups of activities that should be considered as part of AIeR in terms of content. In simpler terms, once thematic subsets of activities are detected within the AI landscape thematic areas, we further consider for this work on AIeR those presenting elements of continuity with the robotics technologies. This approach allows us to expand the boundaries of our specific investigation regarding the AIeR in order to increase the accuracy and precision of the findings, and to reveal how different AI thematic areas are intertwined. In addition, it clearly allows us to stay coherent and consistent with respect to other analytical initiatives based on AI TES2020.

In the last stage, an additional in-depth exploration of a specific part of the AIeR landscape has been performed. This further analysis allows the identification of five thematic areas related to the "AIeR Industry" subdomain. These activities mainly come from the "AI services" thematic area. Although the provision of services is the main type of activity detected in this AI thematic area, a larger share related to the production/commercialisation of goods is detected (instead of services) when we consider those activities that also belong to AIeR. This is why, from an analytical point of view, we use a broader label, i.e., "AIeR Industry". Also, apart from its importance as a part of the economy closest to the market, the "AI Services" thematic area includes the highest number of AIeR activities in the whole AI landscape. ([10])

The proposed approach shows a few limitations. In some cases, unbalanced figures coming from a data source may be the consequence of specific phenomena affecting the activities that the database collect. In such cases, we adopt ad-hoc solutions, as in the case of priority patent applications reported in the Patstat database. In the last years, patent applications show an extremely large number of AI filings by Chinese players. As confirmed by recent specialised scientific literature ([11]), rather than technological improvements these applications are likely to reflect the impact of a series of national policies aiming at targeting innovation in AI but ending up stimulating opportunistic behaviours. In this case, we applied the criteria of excluding players showing no innovative activity other than a single patent application, considering this a proxy of a possible opportunistic initiative and anyways of a very marginal participation in the AI landscape. Moreover, some of the considered data sources may provide an unbalanced geographical coverage, and the choice of relying on different data sources addresses the need of reducing as much as possible such risk, ensuring the best worldwide coverage in terms of detected players. Finally, further analytical efforts are constrained by the limitation in the information that available data can provide. Further work of refinement and integration of additional information is therefore needed to extend the analysis.

2.2 Boundaries of the AIeR landscape

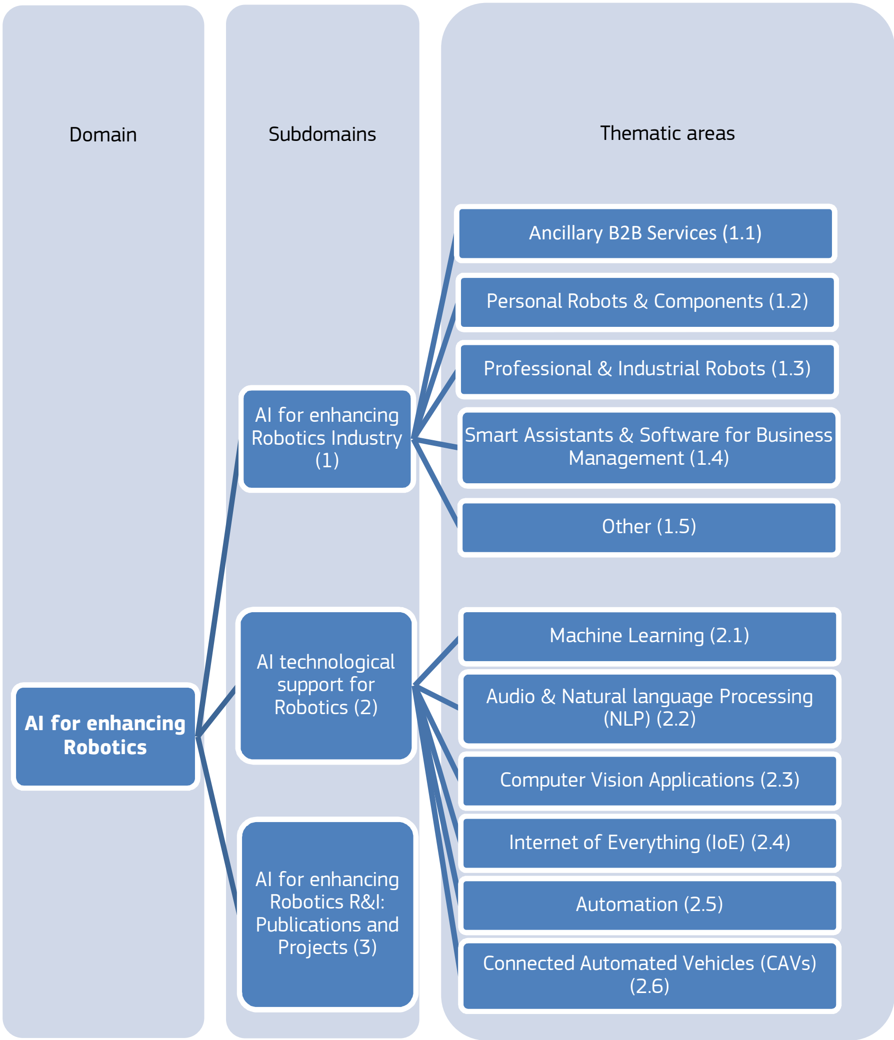
The approach described above enables us to define the AI for enhancing robotics landscape. This can be seen as organised in subdomains, and in some of them thematic areas can also be identified. This classification is synthesised in Scheme 1 and in Figure 2, which also offers a link to the AI thematic areas. The landscape can be classified in three main subdomains, namely (i) AIeR Industry; (ii) AI technological support for Robotics; and (iii) AI for enhancing robotics R&I: Publications and Projects. Based on the activities identified within each subdomain, we can also order them with respect to their closeness to market. The landscape is consequently split in three subdomains referring to different types of economic activities that represent different stages of the economic processes due to their nature.

([10]) For more information about the AI-services thematic area of the AI TES landscape, please see Samoili et al. (2020) TES analysis of AI Worldwide Ecosystem in 2009-2018.

([11]) Several studies analyse the issue of the quality of Chinese patents from different perspectives and metrics and find overall lower performance for Chinese patents, e.g., large citation lag (which indicates lower value of the patent), large shares of domestic citations and of self-citations, alternate effects (depending on the sector) in terms of consequences on firms' productivity, less accurate or shorter description of the innovation, and few number of claims that Chinese patents on average contain (Fisch et al., 2017; Christodoulou et al., 2018; Boeing at al., 2019, Song, 2014).

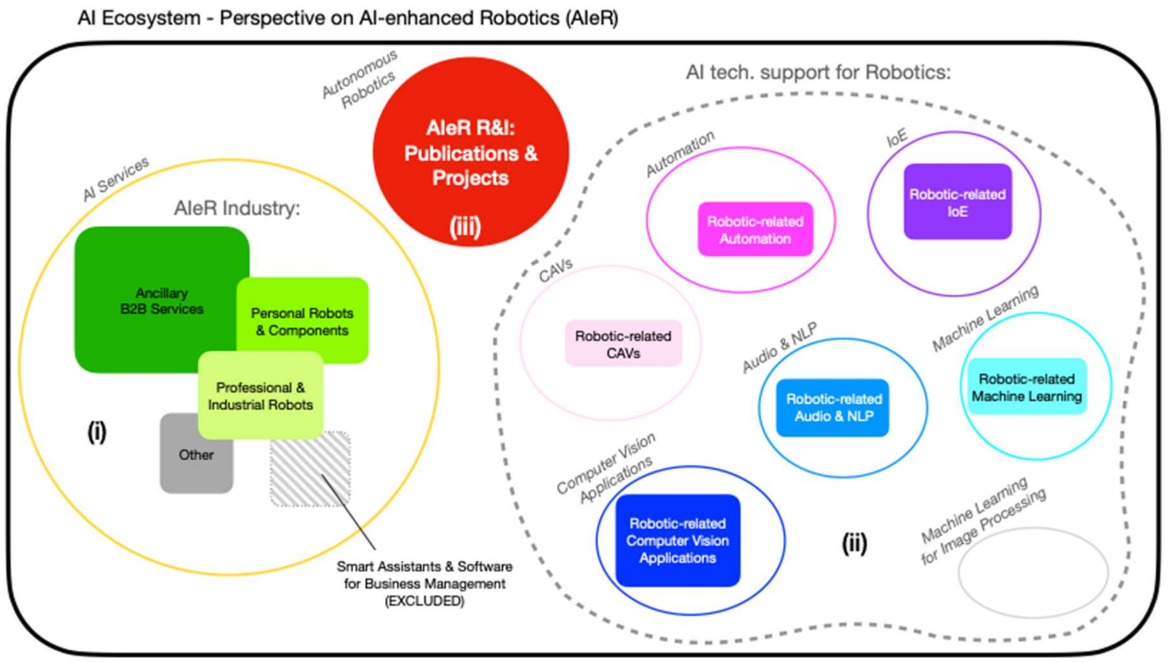
The subdomain that is closest to the market, in the sense that it refers to economic activities already producing and commercialising AIeR products, is the AIeR Industry subdomain (in the Figure 1: green areas, grouped by the orange circle). Then, the AI technological support for robotics subdomain (dashed grey line) includes those activities related to technological developments of AIeR products, e.g., AIeR-related patents. These activities are considered to be less close to the market, as their outputs are not immediately ready for a commercialisation phase, but they need further economic efforts and investments for the initialisation of their production. Finally, the central red circle groups the core of the AI for enhancing robotics landscape (red area), where we see the most advanced research and innovation developments in the field: the AIeR R&I: Publications and Projects subdomain. From an economic perspective, these activities are still far from the implementation phase. In this sense this area is the farthest from the market. Nonetheless, it is a key component as it describes what are expected to be the major future technological evolutions, e.g., the integration of robots in contexts in which humans are then expected to interact with them.

Figure 1. Scheme of subdomains and thematic areas of the AI for enhancing Robotic (AIeR) landscape



Source: JRC elaboration

Figure 2. The AI for enhancing Robotic (AIeR) landscape as part of the AI landscape



Note: The reference to the area "Machine Learning for Image Processing" has been left empty to keep the image complete with respect to the AI field, even though no relevant robotics-related areas were identified there.
Source: JRC elaboration

The conceptual structure of the AIeR landscape is represented in Figure 2, with its three subdomains: AIeR Industry (yellow circle), AI technological support for Robotics (grey dashed area), and AIeR R&I: Publications and Projects (red circle).The number of players corresponding to the different subdomains of AIeR is reported in Table 1, with additional information on geographic location. This to provide a general view on the AIeR domain, while specific analysis is developed in the central sections of the report. Overall, our approach considers AIeR in terms of subdomains (in decreasing order of proximity to the market) and, within them, of AIeR thematic areas.

1. **AI for enhancing Robotic Industry**, ([12]) which includes economic activities (on both goods and services) related to hardware components and software solutions for industrial and service robots. To a large extent this part is composed of business to business (B2B) services, mainly the management of software and platforms for digitalized factories. In general, this subdomain is the most mature part of the robotic landscape, as it deals with products and services that are already on the market. Investigating this subdomain further the following specific thematic areas can be identified:

    1.1. ***AIeR Industry: Ancillary B2B Services*** refers to economic activities related to the implementation of AIeR solutions in contexts where these are not yet implemented, so enabling the integration between robots and old/traditional manually operated systems. In fact, companies willing to incorporate AI-robotics may re-build from scratch their entire production process with brand new AIeR machines, but this can be very costly. Another possibility is provided by businesses, such as those involved in this thematic area, offering solutions that allow the integration of AI-robotic elements in already existing and functioning production processes. Therefore, from an economic point of view, the businesses considered in this thematic area are focused in preparing and offering AI for enhancing robotic-based solutions to other businesses (B2B), rather than focusing in the development and production of some new and very specific AI for enhancing robotic product. Some examples to illustrate the type of economic activity developed by the players offering AI for enhancing robotics solutions for existing businesses (websites accessed on April 11th, 2022) are:

([12]) The "AI for enhancing robotics industry" is mostly identified in the AI thematic area named "AI Services".

- *Provectus Robotics Solutions* (PRS) – Canada: industry leaders in advanced robotic system design, integration and control, located in Ottawa, ON, Canada. PRS delivers robotic products and services to the aerospace, agricultural, industrial, mining, military and security industries (*https://provectus-robotics.com*).

- *Generic Intelligent Machines* - Finland: specialized in design, research, development and integration of intelligent robotic systems, universal 3D mapping and location solutions not fixed in any particular environment or sensor technology, and used in mining, construction, agriculture, forestry, marine, railway and automotive applications (*https://gimrobotics.fi/*).

- *Shinano Kenshi* - Japan: a technology company that provides cutting edge motion control products to various global markets. i.e. Medical, Automotive, Robotics, Industrial and emerging markets. The company is introducing Precision IoT platform, a comprehensive approach from hardware to software providing business value proposition at competitive cost. The comprehensive solution includes identification and integration of application specific sensors, design and development of affordable gateway boards, advance analytic software enabling to track and predict, and storage of big data in clouds/on-premise (*https://us.aspina-group.com/en/index.html*).

- *Penta Robotics* – Netherlands: a privately held company, developing high performance parallel robotic solutions. Their goal is to fulfil the demanding market requirements for improving production efficiency, product quality, user friendliness, easy integration and an auspicious return on your investment (*https://pentarobotics.com/*).

1.2. ***AIeR Industry: Personal Robots & Components***, which refers to the set of economic activities mainly producing and commercializing robots whose final users are individuals. These robots are mainly used in private/public life contexts such as managing the domestic environment, or in cities, infrastructures and living areas. As these robots usually rely on some very specific technological solutions (e.g., computer vision in case of surveillance robots), this part deals with the commercialisation of some specific enabling technological components. Some examples to illustrate the type of economic activity developed by the players offering these kinds of products (websites accessed on April 11th, 2022) are:

- *Vectored* – Israel: it is developing an AI robotics personal-attendant that autonomously controls room appliances to meet each user's needs on an optimized or learned-personalized basis (*https://www.vectored-photonics.com*).

- *RoboTerra Inc.* – US: it is an educational robotics company with leading R&D capacity in smart device design cognitive sciences user experience design and gamification in education. The company develops proprietary robotics kits and also cloud platform with gamified contents for learning (web site not reachable).

- *Sunflower Labs* - US/Switzerland: it builds consumer products to design insightful home security. Sunflower Labs produces an autonomous outdoor security system that senses and deters unwanted visitors. Elegant sensors detect motion and vibration differentiating between people animals and cars (*https://sunflower-labs.com*).

- *Parkki* – France: it designs smart parking solutions with sensors installed on city lights analysing the situation up to 100m (*https://parkki.fr*).

1.3. ***AIeR Industry: Professional & Industrial Robots***, which mainly refers to economic activities related to the production and commercialisation of AI for enhancing robots to be used for working purposes. These robots may be used in multiple sectors, such as in raw-material extraction, harvesting processes, manufacturing processes, but also rescue and safety activities. This thematic area gathers all economic activities associated with the production of diverse AIeR technologies intended and designed primarily for use in working contexts/environment, e.g., collaborative assembly robots in manufacturing or pick-and-place robots. These robots may seem very similar to the Professional Services Robot (ISO), due to a) their relatively small size, and b) their interactivity with operators. However, their use can be further extended, as they are not thought to be used exclusively by specialists. These AI robots can be used in various industries, and operated by workers with different skills, and/or to work independently in complex environments where people are expected to be present. Some examples of players linked to these economic activities (websites accessed on April 11th, 2022), for which it is possible to observe that they mainly focus in the development and production of AIeR products, whose implementation is thought to be in working contexts are:

- *AEye* – US: Developer of robotic vision technologies for autonomous vehicles. The company develops vision system combining LiDar and computer vision with artificial intelligence (AI). They have developed customized software that rapidly scans the scene and identifies objects in real time, thus adding an additional level of safety for the automated vehicle. The company is testing their products with large transportation and heavy industry original equipment manufacturers (OEMs) (https://www.aeye.ai/).

- *Intelligent Flying Machines* – US: Manufacturer of data capturing robots. The company manufactures flying robots with the aim of automating data capture through usage of computer vision. The robots are able to function autonomously in indoor environments, such as warehouses for data analytics and counting purposes (https://www.ifm-tech.com/).

- *Tend AI Inc.* – US: Developer of a cloud robotic software for machine tending. The company is developing a software, which allows a robot arm to start, stop and monitor multiple 3D printers and other devices, removing finished products and initiating new prints. Its solution is powered by artificial intelligence (AI) and is compatible with most collaborative robots, cameras, and sensors (web site not reachable).

- *Springa* – Italy: a start-up of designers and engineers developing autonomous robotic tools for digital fabrication (https://www.goliathcnc.com/).

- *Deep Learning Robotics* – Israel: a technology company specializing in robotics, computer vision and machine learning. They have developed a unique vision-based robotic controller that uses advanced machine learning algorithms to enable robots to learn and replicate tasks by observing humans performing them (https://www.dlrob.com/).

1.4. ***AIeR Industry: Smart Assistants & Software for Business Management***, which refers to the economic activities that provide AI for enhancing services for the management of different aspects of economic activities, with specific reference to customer relationship management. In this case, the concept of "robots" means AI-powered computer applications working as assistants to support complex decisions, make forecasts, and evaluate possible scenarios, and refers to robotics hardware. Since the hardware component is almost completely absent, this area is considered to be scarcely pertinent with the objective of the work. For this reason, we exclude it from the investigation. This point is discussed in more detail at the end of Section 2.3. Some examples to illustrate the type of economic activity developed by the players offering these kinds of products (websites accessed on April 11th, 2022) are:

- *Document Systems* - US: it is a business supplies and equipment company providing document production and management solutions (https://www.docsysinc.com).

- *Information Experience* - Sweden: it provides information management tools for working with 3D BIM models in Augmented Reality to the construction industry. Their cloud service facilitates working with project information from various sources. (https://informationexperience.se).

- *Netis* - Singapore: it builds Navigation system for IT operations and the CrossFlow software platform for realtime intelligence of application services (https://www.netis.com/).

1.5. ***AIeR Industry: Other***, which refers to economic activities using robots for other purposes. For instance, in this thematic area we observe economic activities related to the use of aerial drones and for defence purposes. Some examples to illustrate the type of economic activity developed by the players offering these kinds of products (websites accessed on April 11th, 2022) are:

- *AirGone* - US: it is focused on creating metric mapping information from hyper-economical small unmanned aerial systems (sUAS). AirGon is the airborne micro metric mapping subsidiary of the GeoCue Group. GeoCue Group has been providing workflow and production solutions for sensor-based mapping since 2003 and it has a long history in providing tools and technology used in creating accurate mapping products from manned aircraft sensor data (*https://geocue.com*)

- *InDro Robotics Inc.* - Canada: it is an Unmanned Aerial Vehicles (UAV) company developing rotary and fixed wing unmanned air vehicles (*https://indrorobotics.ca*)

- *Skye Intelligence* - China: it is an innovative tech startup that aims at building worlds next-generation intelligent Auto-Follow drones (web site not reachable)

- *Innovative Signal Analysis* - US: it is a defense & space company offering signal and image processing solutions (*https://www.signal-analysis.com*).

2. **AI technological support for Robotics**, ([13]) including economic activities that are technologically specific (i.e., related to AI) and connected with robotics in terms of products and services used in the field. These areas are:

   2.1. ***AI tech. support for Robotics: Machine Learning*** refers to all the activities related to the development of ML algorithms which, in this specific case, allow the robots to learn and, therefore, act with some degree of autonomy.

   2.2. ***AI tech. support for Robotics: Audio & Natural language Processing (NLP)***, which is about the development and production of specific hardware components and software programs that make the support of increasingly complex set of activities possible. One of the most important aspects to consider here is the human-robot interaction process, which needs to be enabled by specific physical technologies. Indeed, the ability of the robot to understand and elaborate vocal instructions is crucial.

   2.3. ***AI tech. support for Robotics: Computer Vision Applications***, which is associated with the creation of technologies to process visual information about the surrounding environment which, in this specific case, allows robots to understand the context in which they are located in order to act in it and interact with it. Similarly, to “AI tech. support for Robotics: Audio & NLP” this area is about elements regarding some specific ability that the robots are instructed to have.

   2.4. ***AI tech. support for Robotics: Internet of Everything (IoE)*** which concerns everything that is needed to support the integrated and coordinated activities of multiple intelligent machines which, in this specific case, allows robots to operate in environments in which they work either with other robots or with humans participating in the process. This is a thematic area which is related to the hardware and software technologies that support the continuous data collection, information elaboration and communication procedures that are necessary to realise increasingly sophisticated and precise actions for which multiple and coordinated robotic actors are required.

   2.5. ***AI tech. support for Robotics: Automation*** refers to an area close to robotics but with some substantial differences. While the term “robots” indicates machines that are designed and created to operate under conditions in which human interaction is (at least) possible, “automated machines” are apparatus whose core function is to replicate in the most efficient way some very repetitive tasks. Nevertheless, the integration of AI technologies in automated machines allows the realisation of smart and partially self-regulating processes that may be very cost intensive because of their complexity and the physical resources/inputs involved. For this reason, the boundaries between “robotics” and “automation” are in many cases blurred and, depending on the initial perspective, a specific activity may be defined as more related to one instead of the other. Because of the continuity between these two areas, we can capture the part of “automation” that is closest to “robotics”.

([13]) “AI technology for robotics” includes robotic-related activities mainly initially classified in the AI landscape under thematic areas different from “autonomous robotics” and “AI services”.

2.6. ***AI tech. support for Robotics: Connected Automated Vehicles (CAVs)*** refers to vehicles that can move and circulate with different degrees of lack of supervision. In the specific case of the robotic-related CAVs, this refers to machines for which the required supervision is minimal and only a few initial instructions are required to move through long and complex paths. Clearly, this requires several hardware and software technologies to continuously collect and process the information about the surrounding environment.

3. **AI for enhancing Robotics R&I: Publications and Projects**, in recent years, AIeR has been subject of a major development effort, as witnessed by the number of EU Projects which to varying degrees target it. With respect to activities related to research projects, a classification in line with the official 'pillars' of EU funding is also offered. For H2020, the main pillars are: (a) Excellent science, (b) Industrial leadership, (c) Societal challenges, (d) Spreading excellence and widening participation, (e) Science with and for society, and (f) Euratom. For FP7, the main programs were: (a) Cooperation, (b) Ideas, (c) People, (d) Capacities, and (e) Euratom.

Table 1 (below) shows the number of players divided by the technological subdomains and thematic areas identified and discussed above, and by geographical macro-areas, including all types of activities (such as EU-funded projects).

It should be noted that players whose involvement is exclusively participation in AI-related EC-funded projects (i.e., FP7/H2020) are not included in the mentioned numbers.

Indeed, thanks to EU-funded Projects (i.e., FP7/H2020), there are players that enter in the AI for enhancing robotics domain. However, without these projects, these players will not be part of such technological domain, as no other activities related with AI for enhancing robotics can be tracked for those players. The grey row reports the addition of players for the EU27, in the case EU-funded projects are considered. When the analysis targets the worldwide AIeR domain/landscape, the players highlighted in grey are not considered, as this would bias the results by increasing the number of EU27 players in consideration of public funding initiatives while similar initiatives not taken into account for other parts of the world.

When taking into account EU-funded projects, a few other areas not located in the EU27 but allowed participating to different extent to EU programmes see an increase in their number of players. Figures change most remarkably for the UK, which goes from 806 players to 1,256, for Other European countries, going from 358 to 735, and Middle East, from 314 to 489.

Table 1. Number of players in the AI for enhancing Robotic (AIeR) landscape, by thematic and geographical area ([14])

Main Areas of the ecosystem	(1) AIeR Industry				(2) AI technological support for Robotics						(3) AIeR R&I: Publications & Projects	TOTAL
N. of Players	(1.1) Ancillary B2B Services	(1.2) Personal Robots & Components	(1.3) Professional & Industrial Robots	(1.5) Other	(2.1) Machine Learning	(2.2) Audio & NLP	(2.3) Computer Vision Applications	(2.4) IoE	(2.5) Automation	(2.6) CAVs		
US	1,993	990	480	215	60	117	80	40	10	2	408	**4,124**
China	399	126	71	6	718	437	765	804	538	4	101	**3,021**
EU27 (without EU projects)	936	413	187	74	35	49	27	28	17	5	289	**1,970**
EU27 (effect of EU projects)	*107*	*87*	*32*	*0*	*0*	*1*	*0*	*42*	*0*	*255*	*4792*	***4,893***
UK	355	218	99	49	8	28	11	14	3	26	526	**806**
India	240	162	43	26	3	5	1	0	1	0	31	**507**
Canada	195	81	40	15	5	9	2	1	0	0	43	**375**
Other Asian countries	157	84	29	12	22	25	24	15	4	1	58	**383**
Other European countries	195	92	33	8	2	15	8	5	8	20	407	**358**
Middle East	129	89	48	4	4	10	3	1	1	7	209	**314**
Japan	93	35	19	8	18	55	29	8	4	2	58	**270**
Other American countries	91	69	21	9	5	8	2	3	7	1	46	**236**
South Korea	33	13	17	3	40	62	43	38	13	7	29	**224**
Oceania	95	44	15	9	4	1	4	3	0	0	41	**197**
Africa	68	38	7	12	2	3	2	2	3	0	41	**147**
Sum by Thematic Area	**5,086**	**2,541**	**1,141**	**450**	**926**	**825**	**1,001**	**1,004**	**609**	**330**	**7,079**	**17,825**

Note:
(1) The sum of players detected by Thematic Area does not match the Total number of players finally involved in the landscape, as reported in the last column of the table. In fact, the same player may be detected in multiple Thematic areas but is counted just once when considering everything together.

(2) The column totals include the players that are located in EU27 due to their participation in relevant EU-funded projects (grey row). Similar local funding instruments are not considered for other geographical areas. If the mentioned players identified by participation in EU-funded projects are added to the total, this would rise to 19,004.

Source: JRC elaboration

2.3 Matching existing classifications with the areas of the AIeR landscape

The modern concept of robot was developed in the 1950s, when the first industrial robots started to be designed. They became operational starting from the subsequent decade and over the years their development has taken several paths: from implementation in factories, to defence uses and on to space exploration. The last 20 years have witnessed a transition from industry to broader areas of human activities, with implementations for civil uses such as assisting with surgery, self-driving vehicles or playing chess games.

- The current classification of robots mainly relies on two categories:

(i) **Industrial Robots**, which the International Organization for Standardization (ISO) defines as "automatically controlled, reprogrammable multipurpose manipulator programmable in three or more axes", and

(ii) **Service Robots**, which ISO defines as robots "that perform useful tasks for humans or equipment excluding industrial automation applications". Then, a second level of distinction is usually adopted to separate according to applications:

(ii.a) **Personal Robots**, which are usually used by non-specialised individuals for non-commercial tasks, and

([14]) Thematic areas are represented in decreasing order of size (with respect to number of identified players).

(ii.b) **Professional Robots,** which are usually employed for commercial/working tasks and require more specific skills to make them operative.

This standard categorisation can be matched to the one resulting from the analysis of the landscape, while keeping in mind the following points:

- As discussed in the introduction, the domain that we address in this study refers exclusively to robots supported by AI. Therefore, robotic machines that operate with many degrees of mobility but are 100% programmed or controlled by a remote operator are not considered in the AI for enhancing robotics landscape.

- The thematic area that we label "(1.3) **AIeR Industry: Professional & Industrial Robots**" includes both "industrial robots" and "professional robots'" Traditional industrial robots were exclusively considered as very large and expensive specialised installations (Bauer et al, 2016), which do not make use of AI. Professional robots traditionally correspond to smaller machines, in some cases supporting specialised workers, and they may use AI. The thematic area that we identify refers to all the robots that are used in working contexts, especially manufacturing ones, and we find evidence of smaller robots performing tasks in factories and supporting the physical work of employees. ([15]) This mapping shows that industrial robots seem to be evolving into AI for enhancing ones that are smaller, multi-functions and easily-integrable industrial robots which are (i) suitable for small and medium-sized enterprises (SMEs), and (ii) allow simpler human-robot interactions.

- The thematic area that we label "(1.2) **AIeR Industry: Personal Robots & Components**" mainly refers to what is included in the traditional category of "personal/domestic robots", i.e., robots whose final users are individuals and whose functions are usually related to some living context, such as domestic robots (e.g., vacuum cleaners). However, there are two caveats which must be considered. First, this thematic area mainly includes robots that can be categorised as personal robots, but also some robots that are considered to be professional robots. More specifically, in this thematic area we have robots that are indeed professional, but that mainly operate *on* people, as for instance healthcare robots. Second, since the robots discussed in this thematic area are usually smaller and designed to do some very specific tasks smartly, they are often based on very specific components (for example, robotic systems of surveillance which mainly rely on computer vision technologies). Therefore, when analysing the landscape we can observe several economic activities producing and developing these specific components, grouped together with personal robots, so forming a conceptually single continuous thematic area which therefore differentiates them from the more "traditional" definition.

- The thematic areas labelled with the prefix "(2) **AI tech. support**" correspond to the activities of many players whose main business is not about autonomous robotics, but are relevant as support to robotics. More specifically, all the technologies where the robots need to interact with the physical reality (computer vision, audio & NLP, etc.,) have very specific properties. In particular, the development of physical hardware and specific AI algorithms requires expertise and accumulated knowledge. This is the case, for instance, with large Korean enterprises actively working in the field of electronics, such as Samsung or LG. Their business is mainly in the development of specific electronic technologies but now, with a vast accumulated knowledge in AI, they are using their expertise to move on the production of AI for enhancing robots.

- Finally, the two thematic areas of "(1.1) **AIeR Industry: Ancillary B2B Services**" and "(1.4) **AIeR Industry: Smart Assistants & Software for Business Management**" are showing interesting evolutions of the landscape. The former includes the economic activities providing services and solutions to integrate robots in a selected operational context. This is a key area as it consists of the players that allow existing businesses to be supported in the transition towards more robotised environments (such as factories, hospitals, public spaces, etc.). These players are, to some extent, enabling the diffusion of the technology. The second one, "(1.4) AIeR Industry: Smart Assistants & Software for Business Management", also refers to businesses providing services for other businesses. However, here the focus is not on making some robotic device operational in a new environment, but

([15]) Considering the standard classification, professional robots are normally smaller machines that are typically used only by professionals (i.e., medical doctors). Evidence shows that many small robots are used in factories, where "traditionally" only larger robots were expected to be found. Small (AI for enhancing) robots seem to become more adapted to be used for multiple purposes by workers in manufacturing.

on the provision of ad-hoc robotic assistants that help to deal with different aspects, evaluations, decisions, scenarios etc., related to business management. These two areas, which are not covered by the standard classification introduced in the beginning of this section, are emerging in the AI for enhancing robotics landscape. However, while the first one (i.e., "(1.1) AIeR Industry: Ancillary B2B Services") covers activities that are closely related to the domain of Robotics from an economic point of view, the second one (i.e., "(1.4) AIeR Industry: Smart Assistants & Software for Business Management") is less evidently linked to the traditional concept of robots because the corresponding services rely on robotics products. In fact, while these smart tools are able to interact with humans, which would allow them to be considered as robots, they have no physical dimension and therefore cannot act or move in the real world. In the end, to be more consistent with existing literature and to be more policy relevant, we exclude the activities involved in this last category (i.e., "(1.4) AIeR Industry: Smart Assistants & Software for Business Management").

- The following scheme presents all the subdomains and thematic areas that emerge in the AIeR landscape as well as the main keywords identified for each of them.

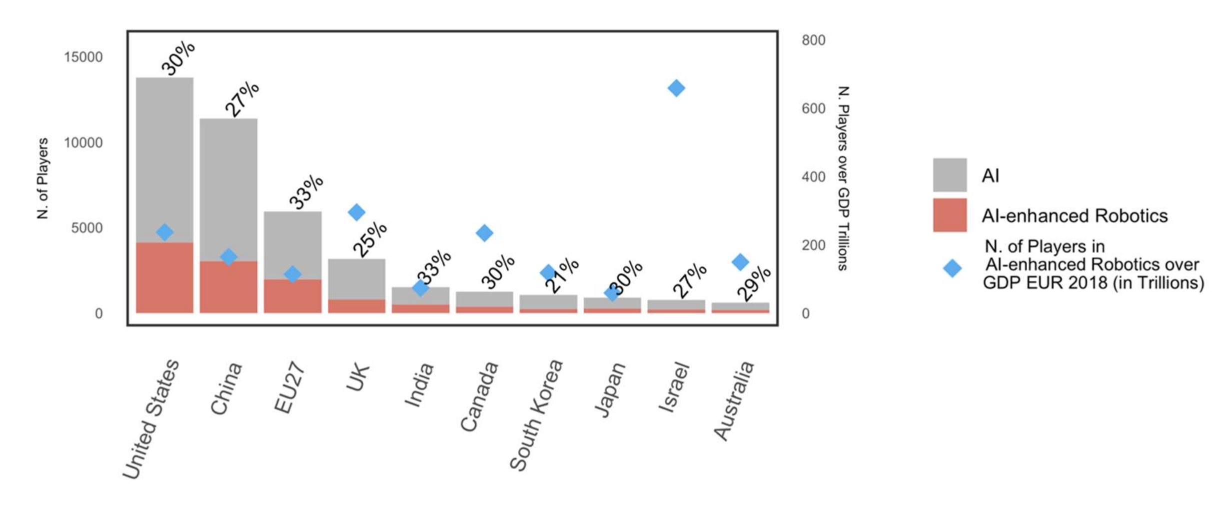
3 International AI for enhancing robotics landscape

In this section we present the worldwide distribution of players in the AI for enhancing robotics landscape, as well as their characteristics. We then close the section by proposing a comparison by country and world region with respect to their Revealed Comparative Advantage (RCA ([16])).

3.1 AI for enhancing robotics in the global AI landscape

Figure 3 shows the numbers of AI players in AI for enhancing robotics by country, compared with the total number of AI players by country. It is remarkable that AI for enhancing robotics players account for almost 30% of the total number of AI players. This percentage is rather consistent across countries and world regions. This reveals that an important proportion of the players that are active in AI are also involved to some extent in the robotics domain, and that the two technological domains have a considerable overlap and mutual links.

Figure 3. Distribution of AI for enhancing Robotic (AIeR) players by country



Notes:
(1) EU-funded projects are not considered in this graph. EU27 is aggregated as one geographic area.
(2) Percentages on top of the bars indicate the number of players in AI for enhancing robotics (out of the total number of players in AI)
(3) Blue points indicate the ratio determined by No. of players in AI for enhancing robotics divided by GDP EUR 2018 (in tens of trillions)
Source: JRC elaboration

The **US,** which is the leading country in AI in terms of number of players, also confirms a strong presence in AI for enhancing robotics. This stands relatively both with respect to AI, and with respect to AI for enhancing robotics: 30% of US AI players are also part of AI for enhancing robotics, and the US players in AI for enhancing robotics represent the 32% of all the AI for enhancing robotics players worldwide.

China, which holds the second position in the AI landscape in term of number of players, is also second in the AI for enhancing robotics landscape. However, it shows a lower degree of involvement than that of the US and the EU, with 27% of AI Chinese players active in AI for enhancing robotics (against 30% for the US and 33% for the EU27). In addition, most Chinese players appear to have a less direct involvement in the field, with many of them being mostly involved in very technology-specific thematic areas such as computer vision, machine learning, and IoE. Therefore, their relationship with AI for enhancing robotics appears to be mainly in the production or provision of specific parts and components for robotics. China is the global leader in the “automation” thematic area of the AI TES landscape (IFR, 2017, 2021a; Robotics & Automation, 2021) and, therefore, while its role in AI for enhancing robotics is indeed important, it is qualitatively different from the one of the US and the EU, meaning that according to the AI TES landscape, China is mainly specialised in “automation” rather than the “autonomous robotics” thematic area.

([16]) Balassa, B. (1965). Trade liberalisation and “revealed” comparative advantage 1. The Manchester School, 33(2), 99–123.

The **EU** holds the third place globally in terms of the number of AI for enhancing robotics players, as it does with respect to AI players. Nevertheless, the pervasiveness of AI for enhancing robotics in the EU is strong, since about 33% of AI players are involved in AI for enhancing robotics, a percentage that is higher than in China (27%) and the US (30%). This insight confirms the relevant role of EU Member States in AI for enhancing robotics and supports considering the EU as global leader in the domain. In addition, this percentage of 33% does not consider participations in H2020 and or FP7 projects (to allow for comparison with non-EU countries).

In the **UK** 25% of AI players are involved in AI for enhancing robotics players, which is 8 percentage points lower than in the EU. Considering the ratio of the number of players divided by national GDP (blue dots in Figure 3), UK presents a high number of players in AI for enhancing robotics. However, this is not a characteristic specific to AI for enhancing robotics but is rather a general point regarding UK and the whole AI field, meaning that in general the UK players are quite active in the AI field.

An interesting discussion is triggered by the position of **South Korea** in terms of number of players. The country is considered the most robotised country in the world, since, for instance, it counts 850 robots per 10,000 manufacturing employees (IFR, 2019; Statista, 2021b). However, this does not necessarily mean that the very large number of robots used in the country is supplied by Korean firms. In fact, "Korean robot manufacturers have had a very weak presence not only in the global market, but also the domestic market until now" (Minkyo Kim, 2021) which has made Korea lag "behind China, Japan, the United States and European nations in terms of software and hardware" (Moon Jeon-il, 2021). Therefore, despite its very high density of robots, South Korea is not currently a top country in respect of their production, and it depends a lot on imports, mainly from Japan and European countries. It is therefore not surprising that we observe an involvement in AI for enhancing robotics that accounts for only 21% of its own AI players. There are, however, several elements regarding, for instance, the population dynamics, government policies and the structure of local industry which suggest South Korea is at an early stage of development, and that the Korean robotics industry may soon become a major player. ([17])

In **Japan,** 30% of AI players are also part of AI for enhancing robotics, like in the US. Japan is considered one of the world's top countries in robotics, both with respect to the quantity of the robots it produces as well as their quality. Japan leads both in terms of installed robots and exported ones (IFR estimates that in 2016 Japan exported half of the industrial robots supplied that year (IFR, 2021d). Over the years, economic and cultural factors have pushed Japanese developers to create very advanced robots that are able to interact with humans, such as "Asimo" by Honda, "Pepper" (developed originally in France by Aldebaran before the company was bought by SoftBank Robotics), and "Kirobo" ([18]) (i.e., the first robot astronaut). Apart from these high-tech humanoids, robots in Japan are widely used in factories alongside human employees, as well as in private life and in public contexts such as hospitals. The vast knowledge accumulated by Japan in the field has also pushed the EU to develop specific partnerships with this very strategic partner. Some recent examples are the CARESSES and e-VITA projects (Caresses robot, 2021; CORDIS, 2021). The large percentage of Japanese AI players involved in AI for enhancing robotics (30%) attests to the remarkable synergy between AI and Robotics. In addition, the comparatively small number of AI for enhancing robotics players is likely to be due to a more advanced stage of the sector, as several Japanese companies have already strongly consolidated their position, thus leaving less room for smaller companies.

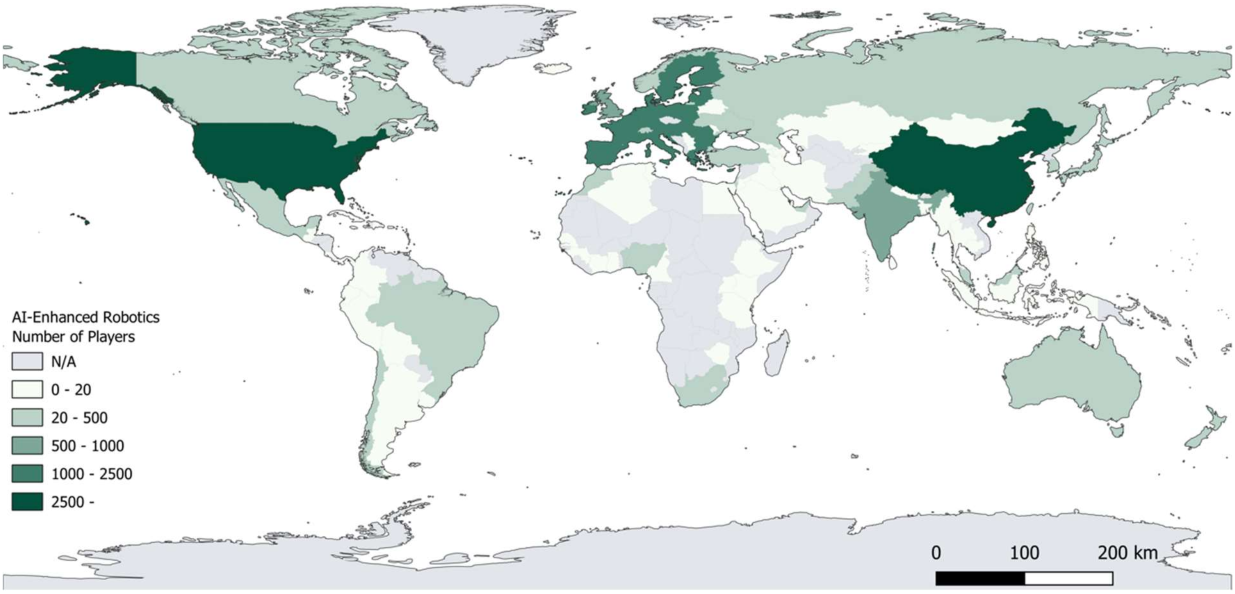
([17]) We report that: (i) South Korea has strongly invested in the use of AI in order to develop smart cities, and now it is trying to use care-robots in order to face a problem of aging population; (ii) the South Korean robotic industry receives consistent support from the government, by means of the five-year Robot Basic Plans or by the formation of incubators like the Korea Association of Robot Industry (KAR) and the Korea Institute for Robot Industry Advancement (KIRIA); (iii) large Korean companies, like Samsung and LG, are combining their knowledge in cutting-edge AI software with innovative hardware to definitely enter in the robotic market with care products and, more in general, are showing interest for this segment, as is also testified by the recent acquisition of Boston Dynamics by the Hyundai Motor Group (December 2020).

([18]) Kirobo has been developed by a collaborative effort between Dentsu, the University of Tokyo's Research Center for Advanced Science and Technology, Robo Garage, Toyota, and JAXA (Japan Aerospace Exploration Agency).

Finally, the case of **Israel** is worth mentioning. It shows a large percentage of AI for enhancing robotics players over AI players is observed (27%), with also a very high ratio between AI for enhancing robotics players and national GDP. This indicates a relatively important role of AI for enhancing robotics, despite of the comparatively small size of the national economy.

Figure 4 displays also in graphical terms the distribution of AI for enhancing robotics players around the world.

Figure 4. Map: Worldwide distribution of players

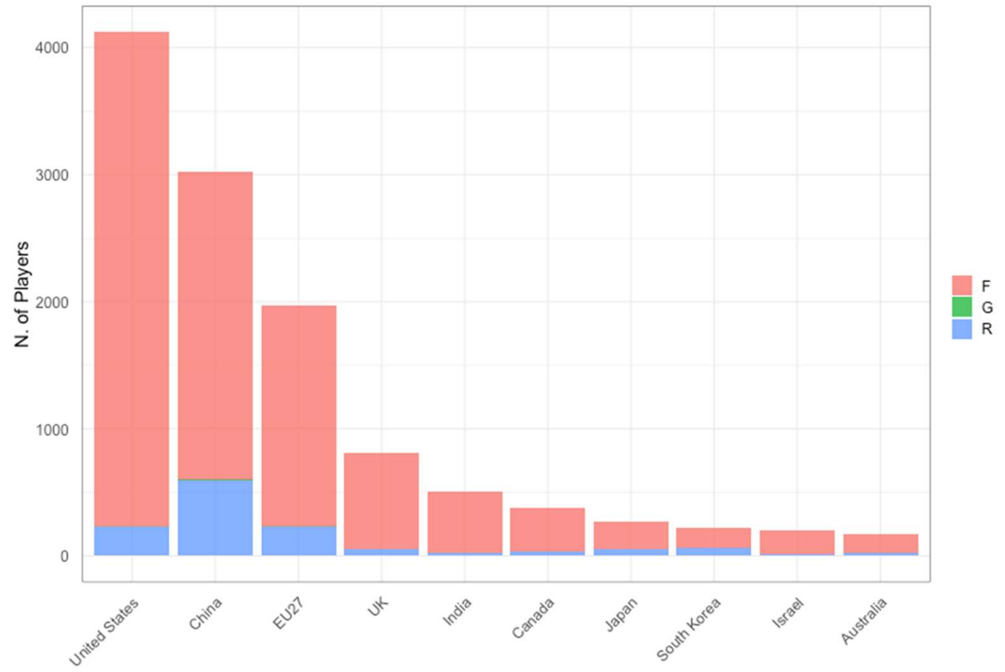


Notes: EU-funded projects are not included. EU27 is aggregated as one geographic area.
Source: JRC elaboration

3.2 Composition of AI for enhancing robotics players worldwide

After having discussed the importance of the AI for enhancing robotics landscape with respect to the AI landscape, we now explore its composition in terms of organisation types and thematic areas.

Figure 5. Number of players and breakdown by organisation type



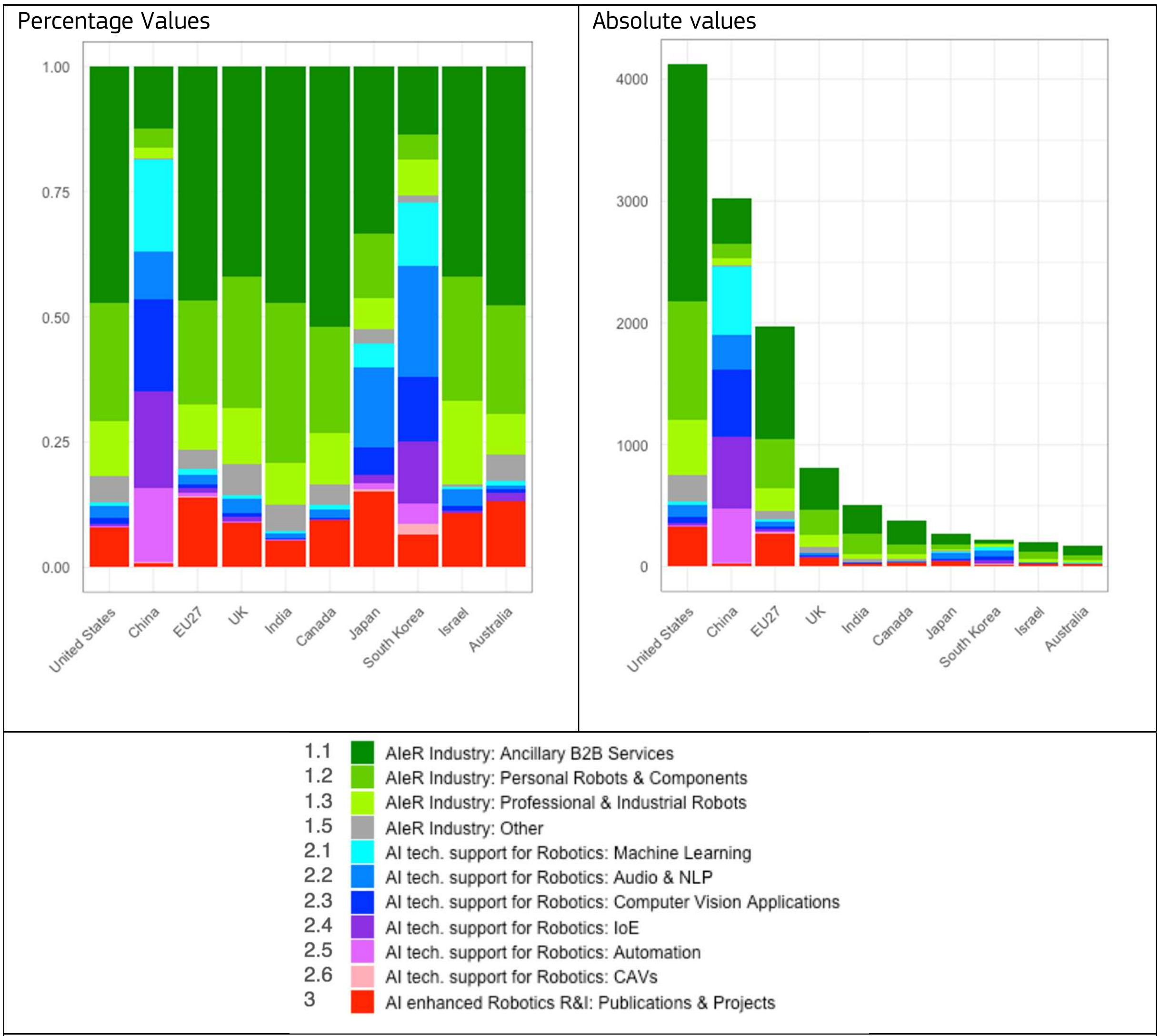
Notes:
(1) EU-funded projects are not included in the worldwide comparison. EU27 is aggregated as one geographic area.
(2) F: firms, G: governmental institutes, R: research institutes
Source: JRC elaboration

Figure 5 provides an overview of the number of AI players by country and organisation type in AI for enhancing robotics worldwide (firms, governmental institutes, or research institutes). We observe that the AI for enhancing robotics landscape is mainly dominated by firms. Nonetheless, some differences are present. The percentage of research institutes(R) that are active in the domain is very large in China (almost 20%), and robust in the EU27 (10%). The US also has many active research institutes in the domain (blue bar), but in percentage terms this represents only 5% of the active players in AI for enhancing robotics. Japan and South Korea both have very large percentages of research institutes involved in the AI for enhancing robotics landscape, with 19% and 29% of the players respectively.

3.3 Thematic areas and Revealed Comparative Advantage (RCA)

The following figure presents the distribution of players by thematic area at country level, both in absolute values and in percentage terms.

Figure 6. Number of players in AI for enhancing Robotics (AIeR) by country and thematic area



Notes: EU-funded projects are not included in the worldwide comparison. EU27 is aggregated as one geographic area.
Source: JRC elaboration

Considering the countries' profiles with respect to their areas of activities, the importance of " (1.1) AIeR Industry: Ancillary B2B Services" appears clearly. This area refers to B2B services mostly for the implementation of specific robot functionalities and the integration of robots and systems into existing processes. The picture suggests that the development of specific solutions and the possibility of interactions among different existing systems, depending on the specific needs, is crucial. At the current state of the technology robots are in fact machines whose functionalities do not fully and automatically self-adapt to the different complex environments (like firms) in which they might be located and used. The need of algorithms, data processing, control platforms, software and communication procedures (among multiple machines) to support robotics is worth considering. Players involved in this area should be considered, to some extent, as enablers of the digital transition. In fact, they make the integration of robotic solutions in already existing contexts possible. This thematic area is very consistent (around 40%) in all the top 10 countries except China and South Korea.

We note the different pattern observed for **China**. Many Chinese players are predominantly involved in very technologically specific AI thematic areas such as Computer Vision, Machine Learning, and IoE. Therefore, their involvement in AI for enhancing robotics is mostly related to the production/provision of specific parts and components for robots. In addition, we can observe the consistent involvement of China's robotics players in "(2.5) AI tech. support for Robotics: Automation", which has many elements of continuity with robotics.

The **US** and the **EU** show a very similar composition, with the EU presenting more players (in percentage terms) involved in "(3) AI for enhancing Robotics R&I: Publications and Projects". The large presence of EU players in the aforementioned area also shows the strong involvement of European players in the development of the technology considering the overall involvement of EU in the AI for enhancing robotics landscape and given that EC-funded projects are not considered in this international comparison.

A large involvement of **Japanese** players in **"**(2.2) AI tech. support for Robotics: Audio & NLP" can also be observed. In addition, as Figure 6 shows, that in Japan there is a large percentage of players active in the most research oriented thematic area, namely "(3) AI for enhancing Robotics R&I: Publications and Projects" (the largest among the top 10 countries). This indicates the active contribution of Japan to the technological development of the domain.

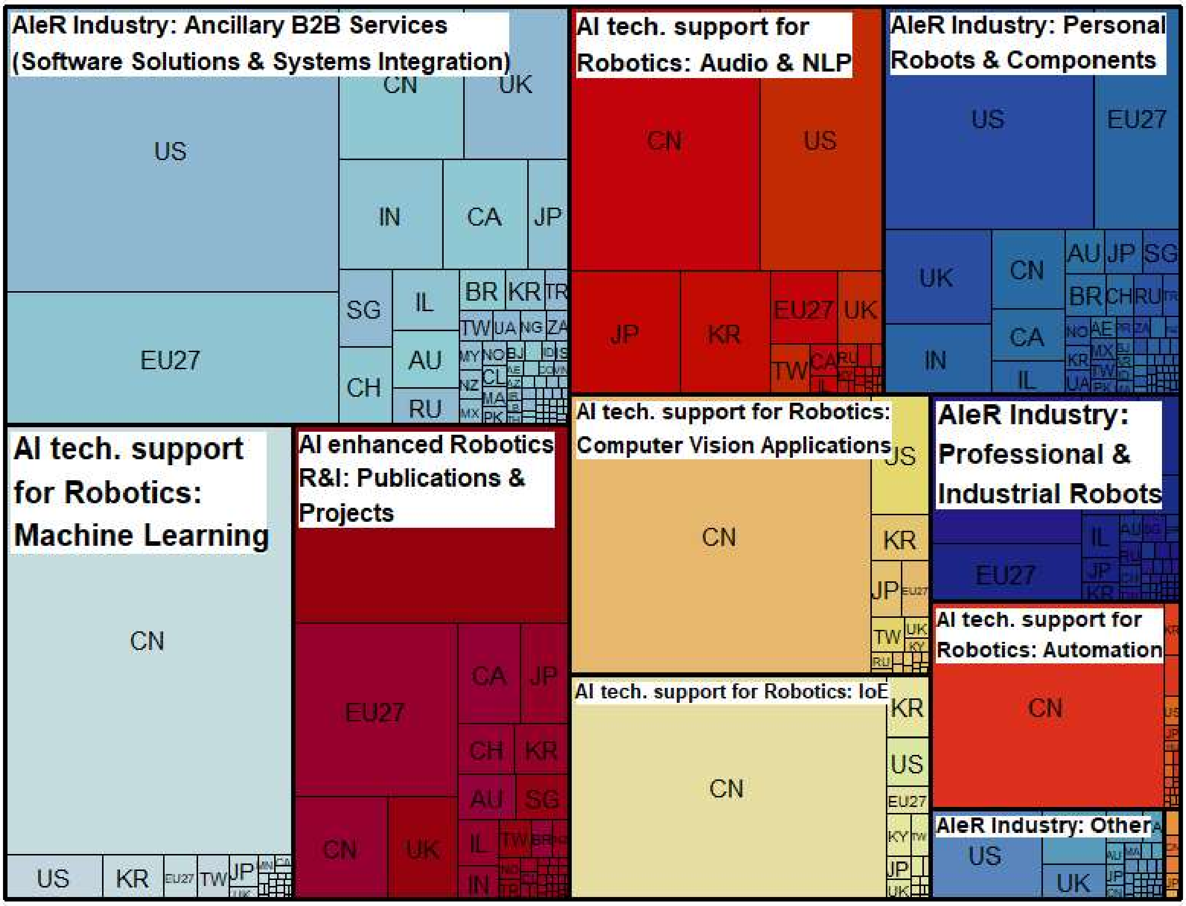
We also observe the strong involvement of **South Korean** players in several areas: "AI tech. support for Robotics: Machine Learning (2.1), Audio & NLP (2.2), Computer Vision Applications (2.3), and IoE (2.4)". This confirms the involvement of the big South Korean high-tech companies (e.g., Samsung, LG) in the development of electronic devices and components. Moreover, South Korea is quickly increasing its production of robots, benefiting from the accumulated knowledge gained from other thematic areas of AI (Samsung, 2021).

We observe that **Israel** has the largest relative percentage of players involved in "(1.2) AIeR Industry: Professional & Industrial Robots", which is the thematic area related to the production and commercialisation of robots employed in working context.

Finally, in local percentage terms, **India** is the country with the largest percentage of players in "(1.2) AIeR Industry: Personal Robots & Component". This country has recently experienced a strong increase in terms of the level of firms' robotisation (Prescient & Strategic Intelligence, 2020).

In Figure 7 (below), the number of activities per thematic area is presented, and the leading position of the US, China and the EU27 in the worldwide landscape becomes evident, occupying the first, second and third places respectively in most of the thematic areas. The UK, Japan and Canada often fill top-5 positions. In addition, China seems to lead in most of the "(2) AI technological support for Robotics" thematic areas, as already mentioned.

Figure 7. Number of AI for enhancing Robotics (AIeR) activities per thematic area worldwide



Notes: EU-funded projects are not included. EU27 is aggregated as one geographic area.
Source: JRC elaboration

To analyse the number of activities and compare countries' activities as shares over other thematic areas and countries further, we employed the RCA indicator. RCA measures a country's specialisation within the AI for enhancing robotics field in comparison with the world average specialisation in that area (see Figure 8 below). With regards to the "(1.3) AIeR Industry: Professional & Industrial Robot" thematic area, **Israel** is ranked first – almost three times above the world average. We report that the EU presented a public-private project in cooperation with several organisations, among them the Israel Aerospace Industries Ltd (TALOS, 2021; TALOS Project, 2021). In addition, through the Sweeper program (Arad et al., 2020; Sweeper, 2021), which involves six partners from four different countries (Netherlands, Belgium, Sweden and Israel), the first market-ready pepper-harvesting robot in the world has been developed. China and India also present active collaborations with Israel. More specifically, China requested Israeli technology developed (to be moved back to Chinese factories) for the mass production of robotic security guards and waiters. India on the other hand, has invested in Israeli companies related to military robot systems and unmanned aerial vehicles (Globes, 2021).

Figure 8 presents the specialisation of the top 10 countries worldwide in number of players, measured through the RCA. The value RCA equal to one represents the world average or average specialisation in the thematic area when all countries are considered. It is the benchmark against which all countries are compared, and it is illustrated by a black line in the plots.

Firstly, all the countries included in the top 10 by number of players (except for China and India) show a specialisation in "(3) AI for enhancing Robotics R&I: Publications and Projects" which is moderately higher than world's average. In this thematic area, which is driven by frontier research publications, Australia, Canada, and the EU are leading with an RCA almost twice the world average. Regarding Australia, we report that it has invested AUD 50 million in its "Smart Cities and Suburbs Program" in order to support innovation in terms of productivity and sustainability (DITRDC, 2018). Canada, on the other hand, is known to have significantly invested in aerospace R&D, a sector that is very connected to robotics.

The EU shows specialisation at or above the world's average in most of the thematic areas, which confirms its relevant role in AI for enhancing robotics. Three of the world's largest producers of industrial robots are located in the EU, although not all are EU-owned (KUKA is German-based but was acquired by the Chinese Midea Group in 2016; ABB is Swedish-Swiss; Comau is Italian). Moreover, besides the support provided by the Robotics Public-Private Partnership, several EU countries promote public and private investment plans for robotics, either directly or indirectly (e.g., France, Italy, Germany, Luxembourg).

As discussed before, many Chinese players are mainly involved in thematic areas related to "Computer Vision", "Machine Learning fundamentals" and "IoE" and "automation". Moreover, in the AI landscape China is the leader in "automation" (Righi et al., 2021). This is a thematic area which is extremely close to the one of Robotics, which makes its role in the AI for enhancing robotics (AIeR) landscape of primary importance (IFR, 2017, 2021a; Robotics & Automation, 2021). South Korea appears 12 times more specialised in "(2.6) AI technological support for Robotics: CAVs" thematic areas than the world average. We recall that even if South Korea is not a top country in terms of robot production, it is ranked on the top positions in Bloomberg NEF's (BNEF) national industrial digitalisation score for 2020 ([19]), and in general it is considered the most robotised country in the world (IFR, 2019), even if it depends to a large extent on imports. South Korea's very remarkable position in "(2.6) AI technological support for Robotics: CAVs" reveals strong connections between the AIeR and the automotive sector. For instance, Hyundai Robotics (which acquired Boston Dynamics in December 2020) is considered a global leader in robotics.

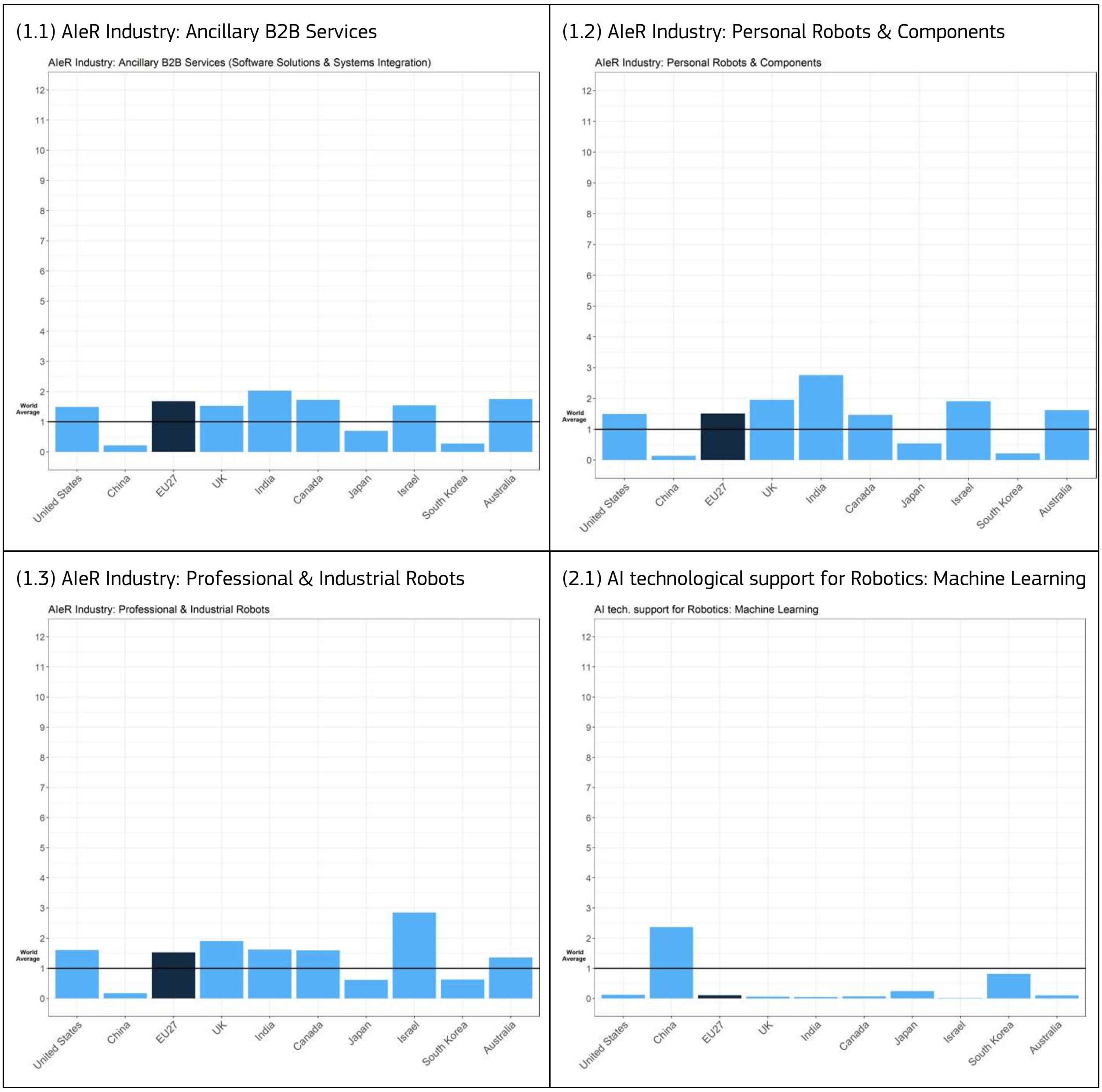
Japan also shows a very consistent specialisation in "(2.6) AI technological support for Robotics: CAVs", and the reasons are likely to be similar to the ones described for South Korea. Many top AIeR Japanese players have direct connections with the automotive industry. Examples of this include Honda (producing ASIMO, which is considered the most advanced humanoid robot), Kawasaki, Yamaha and Denso.

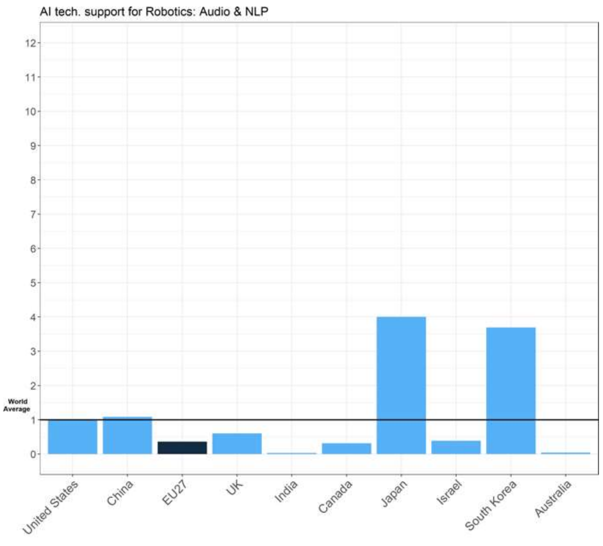
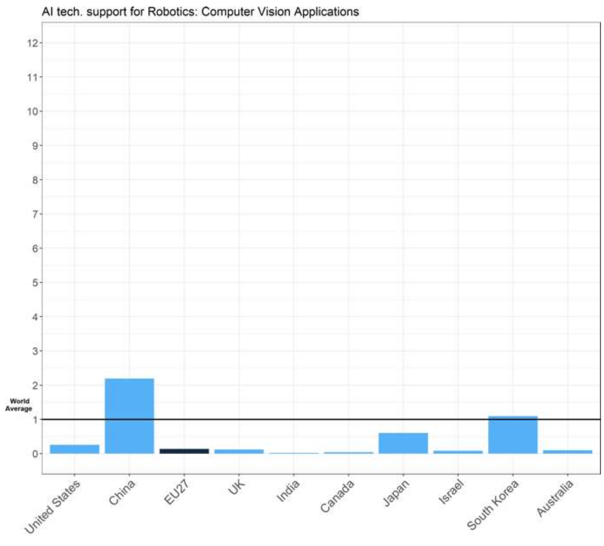
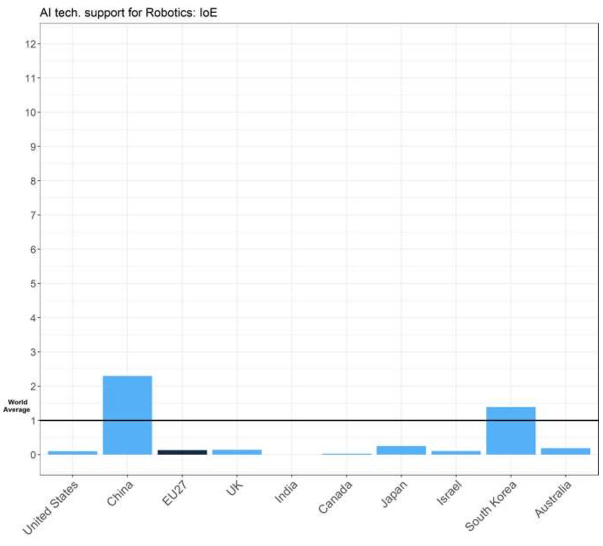
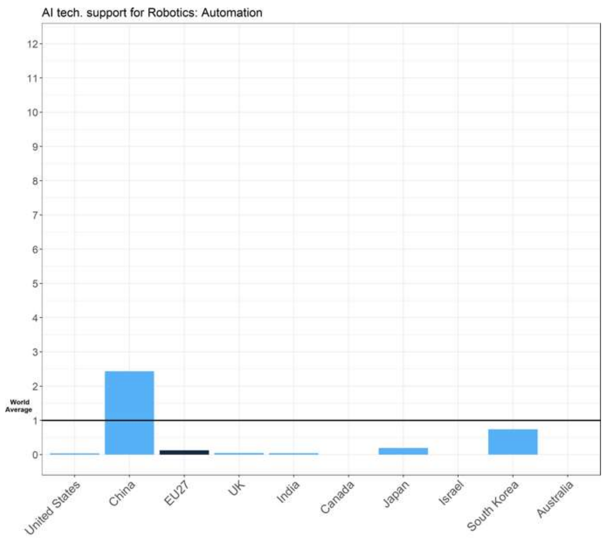
In addition, **Japan and South Korea** show very remarkable specialisation in "(2.2) AI technological support for Robotics: Audio & NLP". In a similar way to what has been previously discussed for "(2.6) AI technological support for Robotics: CAVs", this specialisation is likely to have its origin in the primal business activity of some of the main AIeR players of the two countries. Some examples are LG (SK), Samsung (SK), Sony (JP), whose specialisation in electronic products and devices probably guarantees the necessary know-how to develop ad hoc technologies for AI for enhancing robots.

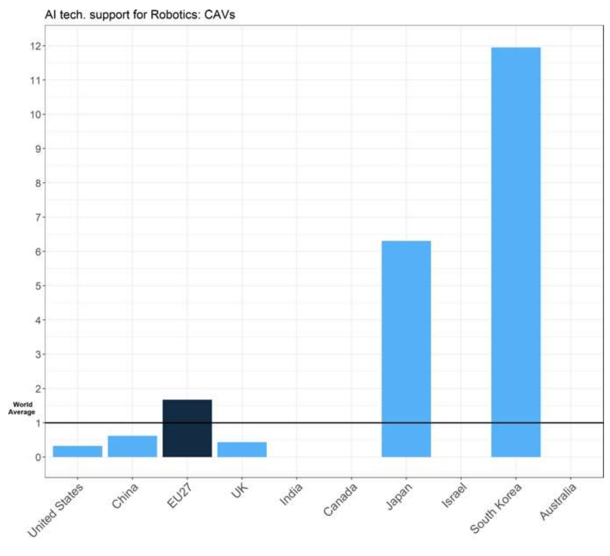
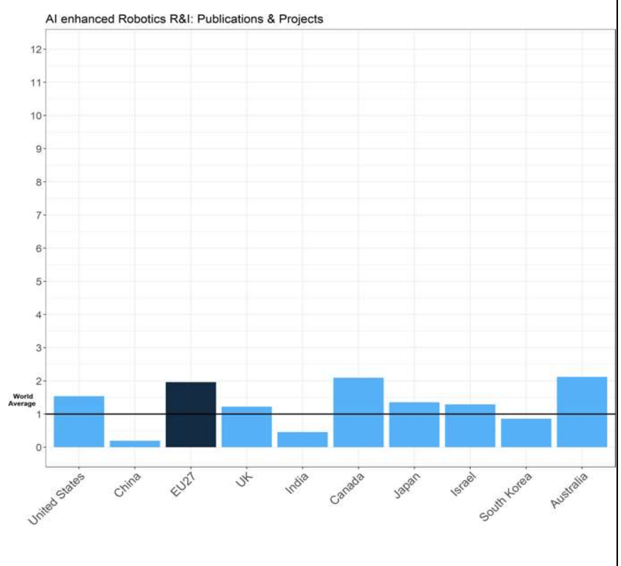
With regards to the "(1.3) AIeR Industry Professional & Industrial Robot" thematic area, **Israel** is ranked first – almost three times above the world average. We report that the EU presented a public-private project in cooperation with several organisations, among them the Israel Aerospace Industries Ltd (TALOS, 2021; TALOS Project, 2021). In addition, through the Sweeper program (Arad et al., 2020; Sweeper, 2021), which involves six partners from four different countries (Netherlands, Belgium, Sweden and Israel), the first market-ready pepper-harvesting robot in the world has been developed. China and India also present active collaborations with Israel. More specifically, China requested Israeli technology developed (to be moved back to Chinese factories) for the mass production of robotic security guards and waiters. India on the other hand, has invested in Israeli companies related to military robot systems and unmanned aerial vehicles (Globes, 2021).

([19]) https://about.bnef.com/blog/south-korea-singapore-germany-lead-bnef-ranking-of-top-digitalization-markets/

Figure 8. Revealed Comparative Advantage (RCA) by AI for enhancing Robotic (AIeR) thematic area worldwide (2009–2020)



(2.2) AI technological support for Robotics: Audio & NLP	(2.3) AI technological support for Robotics: Computer Vision Applications
	
(2.4) AI technological support for Robotics: IoE	(2.5) AI technological support for Robotics: Automation
	

(2.6) AI technological support for Robotics: CAVs	(3) AIeR R&I: Publications & Projects
	

Notes:

(1) EU-funded projects are not included.

(2) EU27 is aggregated as one geographic area.

(3) Thematic areas are presented considering the subparts of the AIeR landscape, in the same order as discussed in Section 2.2, and in decreasing order of number of activities that they include.

Source: JRC elaboration

4 EU27 AI for enhancing robotics landscape

This section provides an overview of the AI for enhancing robotics landscape in the EU27 at the country level. On top of a consolidated private sector in the field, the EC has been supporting the field of robotics for many years in the FPs, especially by means of funded R&I projects and public-private partnerships. In addition, AI for enhancing robotics is considered a key element for the realisation of Europe's digital and green transitions (European Commission, 2021).

Note that FP7 and H2020 are included as data sources in this entire section, besides a few cases that are explicitly mentioned. As some of the detected players may have been considered only because of their participations in EC-funded projects, figures may be different from those referring to the EU in previous sections. However, no bias is introduced as participation in EC-funded projects is equally open to all Member States.

We start this Section describing the roles of the four most important Member States in the field: Germany, France, Spain and Italy. Evidence related to distribution of players and involvement in thematic areas are then discussed.

Germany is considered to be the fifth largest market of robots worldwide. Robot installations have strong connections with the automotive industry since this is the sector with highest adoption rate of industrial robots. In terms of excellence, we recall that KUKA (a German-based company but acquired by the Chinese Midea Group in 2016) is considered a top worldwide player. Recently, it has announced an overall budget of € 350 million for the development of robotics, mainly through the two plans called "High-Tech Strategy 2025" and "Together through Innovation" (December 2020). The High-Tech Strategy (HTS) 2025 sets the strategic objectives for German R&D&I with specific focus on robotic systems for care, and adaptive technologies for society – the intelligent interaction between humans and AI and innovative SMEs (IFR, 2021).

France is very active in trying to bridge research and industry in the field. Concerning this point, we report the creation in 2007 by the French National Centre for Scientific Research (CNRS) of the Groupement de Recherche (GdR) enRobotique, which counts on more than 1,200 researchers and engineers trying to facilitate knowledge diffusion and partnerships. The country benefits also from € 1.75 billion of public support in the framework of "Important Project of Common European Interest" (IPCEI) an EC project for microelectronics, which is among the Key Enabling Technologies (KETs), and an area used for the development of robotics, along with additional financing from the French state, local authorities, and participant industries (IPCEI, 2019). On the part of the private sector, we recall the ECAGroup, a leader in industrial robots and Aldebaran Robotics, which is an innovative company working in the field of humanoid robots whose ownership has been taken by Softbank Robotics (the Japanese company which is leader in the field and that is commercialising the humanoid robot "Pepper").

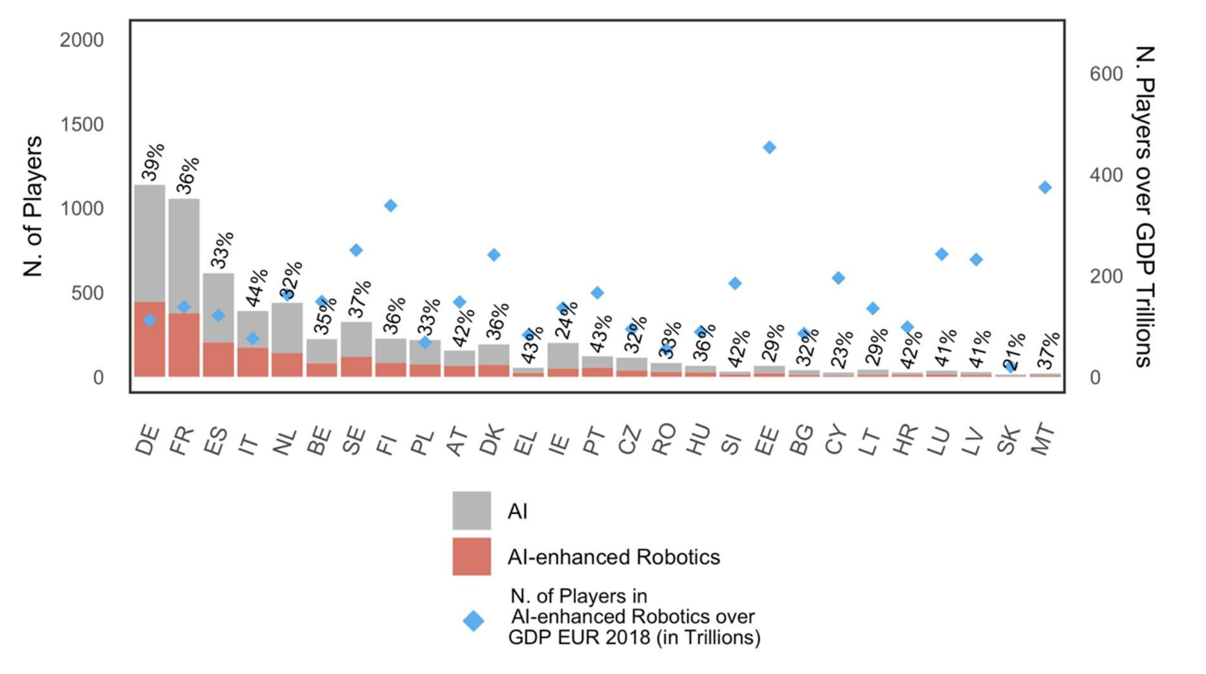
Spain shows recent signals of increasing activity in the field. In particular, we report that in Catalonia the world's first collaborative robot hub was opened in 2019 by the company Universal Robots, whose ownership is Danish. The start-up "br5" is just one example of excellence to highlight the involvement of Spain in most recent trends in the domain, i.e., the shift in the design of traditional industrial robots towards products that are more like professional robots. In addition, one of the most important worldwide enterprises of the field, PAL robotics, is also located in Catalonia. We also remark that Spain is considered an emerging market for robotics and automation, and several foreign countries, such as the US, are looking at the opportunities that may arise (International Trade Administration, 2020).

Italy considers robotics one of its priority sectors, with the Istituto Italiano di Tecnologia having robotics as one of its four research domains and a significant proportion of its patent portfolio, with fundraising exceeding € 60 million for the period 2018–2023 and additional investments such as a public investment fund of € 4.5 million for technology transfer support. In addition, it was recently announced that an Italian Institute for AI (I3A) is planned. This involves the robotics sector and the aim is to become one of the main players for AI in Italy. Finally, one of the most important companies of the sector is based in Italy, namely COMAU. The main headquarters of the company is close to Turin, a city in which strong AI research players (I3A) are also located.

4.1 AI for enhancing robotics in the EU27 AI landscape

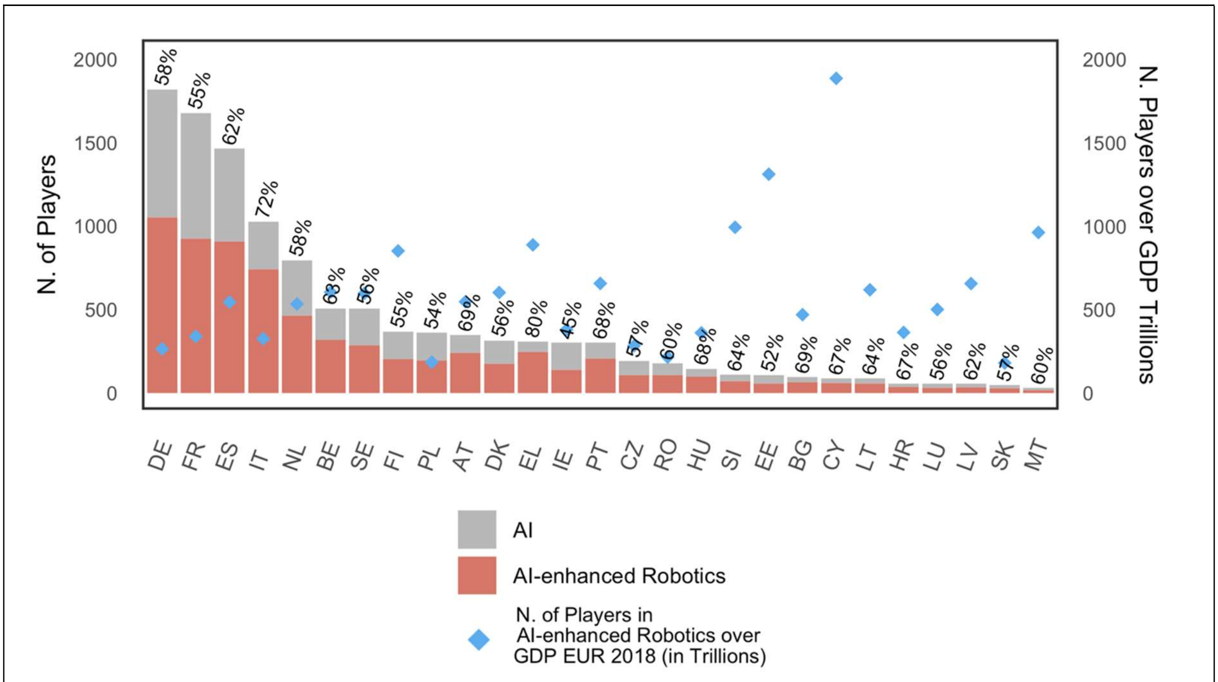
Figure 9 shows that in EU MS AI for enhancing robotics (red part of the bars) count on average about 35% of the total number of AI players, in line with what also discussed with respect to the worldwide comparison.

Figure 9. Number of players in AI for enhancing Robotic (AIeR) thematic areas compared with the total number of AI players in EU MSs (EU-funded projects NOT included)



Source: JRC elaboration

Figure 10. Number of players in AI for enhancing Robotic (AIeR) thematic areas compared with the total number of AI players in EU MS (EU-funded projects included)



Notes:
(1) Percentages on top of the bars indicate the number of players in AI for enhancing robotics (out of the total number of players in AI)
(2) Blue points indicate the ratio determined by No. of Players in AI for enhancing robotics divided by GDP EUR 2018 (in tens of Trillions)
Source: JRC elaboration

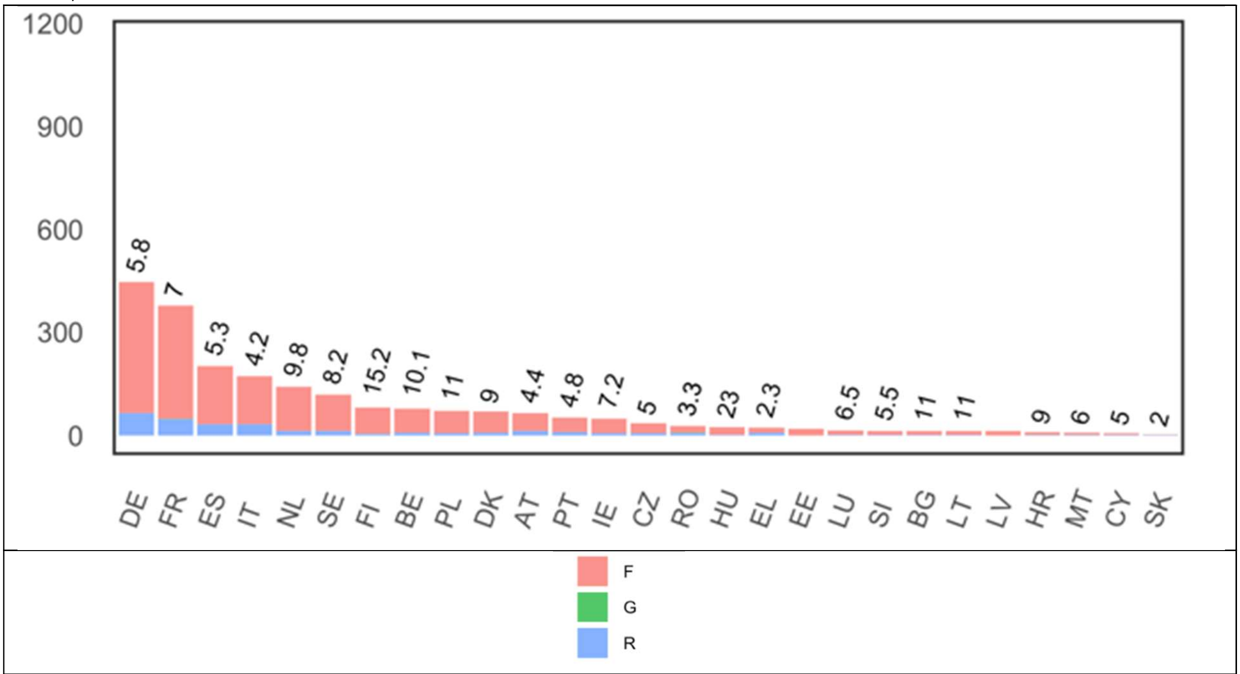
When EU-funded projects are included in the analysis (Figure 10), AI for enhancing robotics players become dominant. This confirms the orientation that AI-related EC-funded projects have had towards robotics. With regards to the leading countries identified in terms of AI for enhancing robotics players (Germany, France, Spain and Italy), the latter two show a remarkable increase in their relative involvement in this domain when EC-funded projects are considered (Spain shifts from 33% to 62% of players in AI for enhancing robotics over players in AI, and Italy from 44% to 72%). It is worth observing that Spain, when considering H2020 and FP7, accounts for almost the same number of players in the AI for enhancing robotics landscape as France, while it has half of France's figure when the EC-funded projects are not taken into account (Figure 9). The increase with respect to countries in lower positions in the ranking is consistent. The two Mediterranean countries also show a consistent presence of governmental institutions, which represent up to 15% of its players in the case of Spain and 17% in that of Italy (Figure 12).

In terms of number of AI for enhancing robotics players divided by GDP (which is a normalisation based on the size of the economy), Estonia, Finland, Sweden, Denmark, Luxemburg, Latvia and Malta stand out when the effect of EC policies is not considered. This reveals a more consolidated presence of economic players that are involved in AI for enhancing robotics independently from EC projects than in other Member States. On the other hand, when EC projects are considered, the most outstanding ratios are observed for Cyprus, Estonia, Slovenia, Malta, Greece and Finland, which therefore appear to be the Member States more reliant on EC funds to sustain the presence of players in AI for enhancing robotics given the size of their economies.

As expected, the ratio between the number of firms and the number of research institutes active in AI for enhancing robotics diminishes when considering EC-funded projects (from Figure 11 to Figure 12). This is the consequence of the objectives of H2020 and FP7, which are research oriented and therefore favour increased participation of research institutions. Interestingly, Spain and Italy, even when not considering H2020 and FP7, show a very low ratio (Figure 11), namely 5.7 and 4.6 firms for each research institute respectively, which basically does not change when considering EC projects. Hence, the AI for enhancing robotics landscape of the two Mediterranean countries seems to be very lively even without EC funds, with a consistently high number of research players. This is likely to favour good connections between industry and research, which in turn can sustain higher innovativeness and competitiveness.

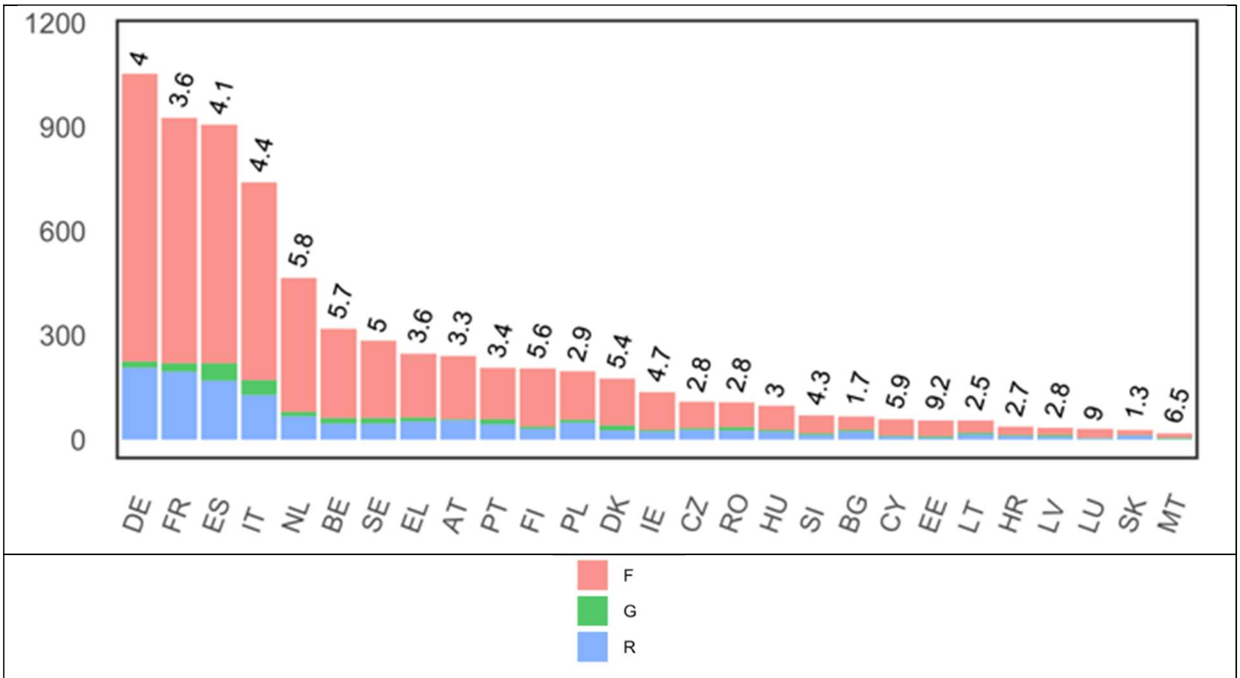
A deeper investigation of players' involvement in the distinct types of activities (i.e., industrial activities, frontier research publications, filing of patents and participations in EC-funded projects), sheds light on the contribution of EU-funded projects in the EU27 landscape. As Figure 10 shows, the number of AI for enhancing robotics players related to EU-funded activities is significant for most of the Member States. Yet, this presence is much higher in the top 4 countries, i.e., Germany, France, Spain and Italy, each of which accounts for nearly 600 players involved in EC-funded projects. Subsequently, the gap with other countries is considerable, as only in the Netherlands is the number of players in EC-funded projects larger than 300. Certainly, the rank reflects the size of the national economies. At the same time, however, the remarkable difference (in terms of number of players involved in EC-funded projects) between the leading groups and the followers suggests that Germany, France, Spain and Italy have more consistent roots in the AI for enhancing robotics landscape, which allows them to be able to propose sound research projects that are selected for funding.

Figure 11. Number of players and ratio in AI for enhancing Robotics (AIeR) by organisation type (EU-funded projects NOT included)



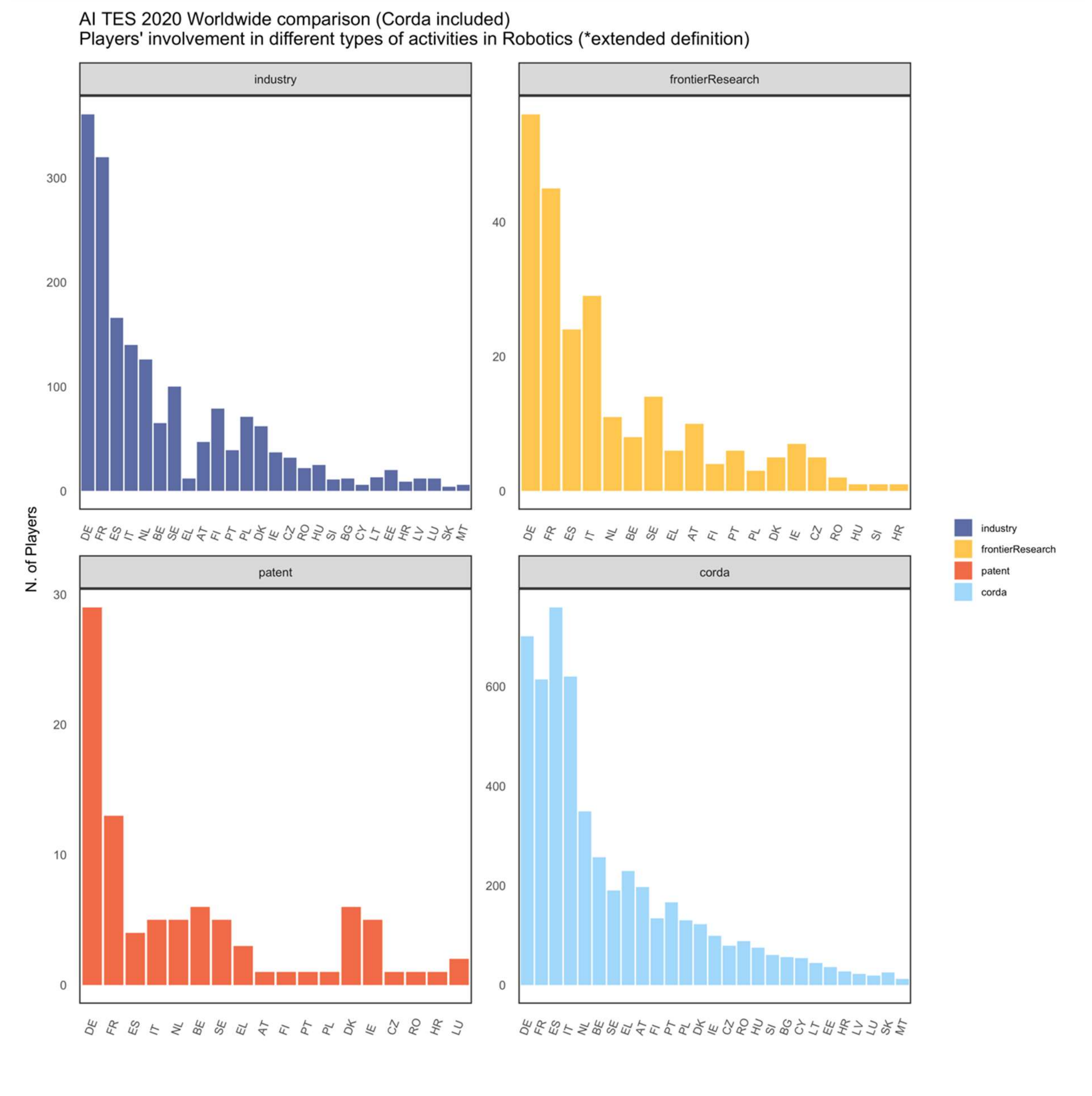
Notes:
(1) EU-funded projects are included.
(2) F: firms, G: government institutes, R: research institutes
Ratios on top of the bars indicate the number of firms per (i.e., divided by) number of research institutes. For example, when EC-funded projects are considered, in Germany (DE), there are 4 firms (F) per each research institute (R), while the same value is 5.8 when EC-funded projects are not considered
Source: JRC elaboration

Figure 12. Number of players in AI for enhancing Robotics (AIeR) by organisation type (EU-funded projects included)



Notes:
(3) EU-funded projects are included.
(4) F: firms, G: government institutes, R: research institutes
Ratios on top of the bars indicate the number of firms per (i.e., divided by) number of research institutes. For example, when EC-funded projects are considered, in Germany (DE), there are 4 firms (F) per each research institute (R), while the same value is 5.8 when EC-funded projects are not considered
Source: JRC elaboration

Figure 13. Number of AI players by EU MS and activity type in AI for enhancing robotics (AIeR)

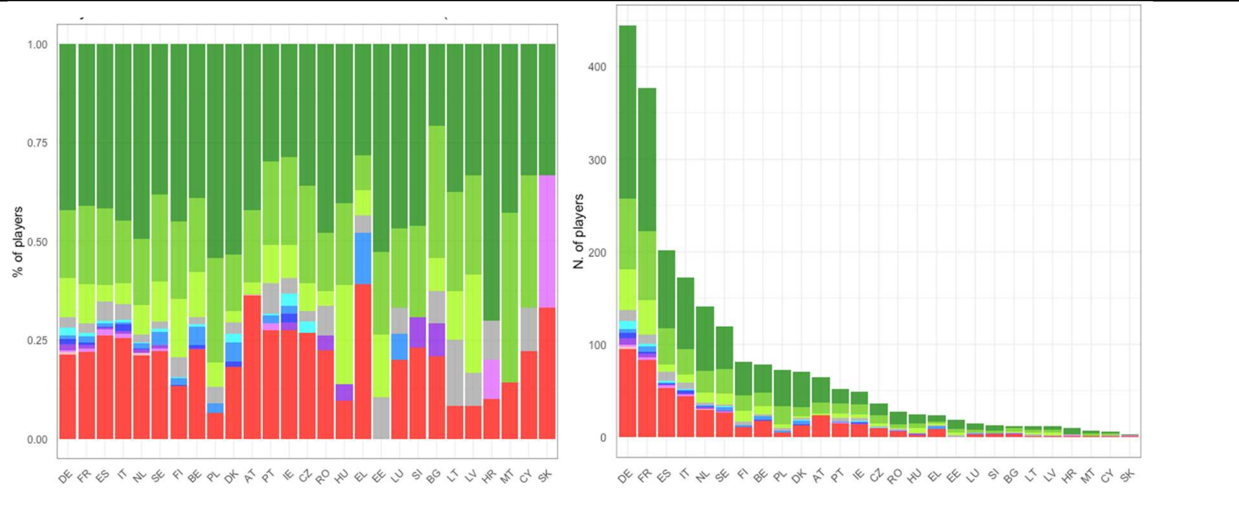


Source: JRC elaboration

The number of players in industrial activities in Germany and France is at least twice as high as in any other Member State, which indicates a more mature economic stage of their AI for enhancing robotics segment. This is also corroborated by a considerable number of players in frontier research publications, which suggests there is a good balance between research and industry. Again, in terms of players involved in frontier research publications, Italy, Sweden, and Austria also present significant values for the overall number of players they have.

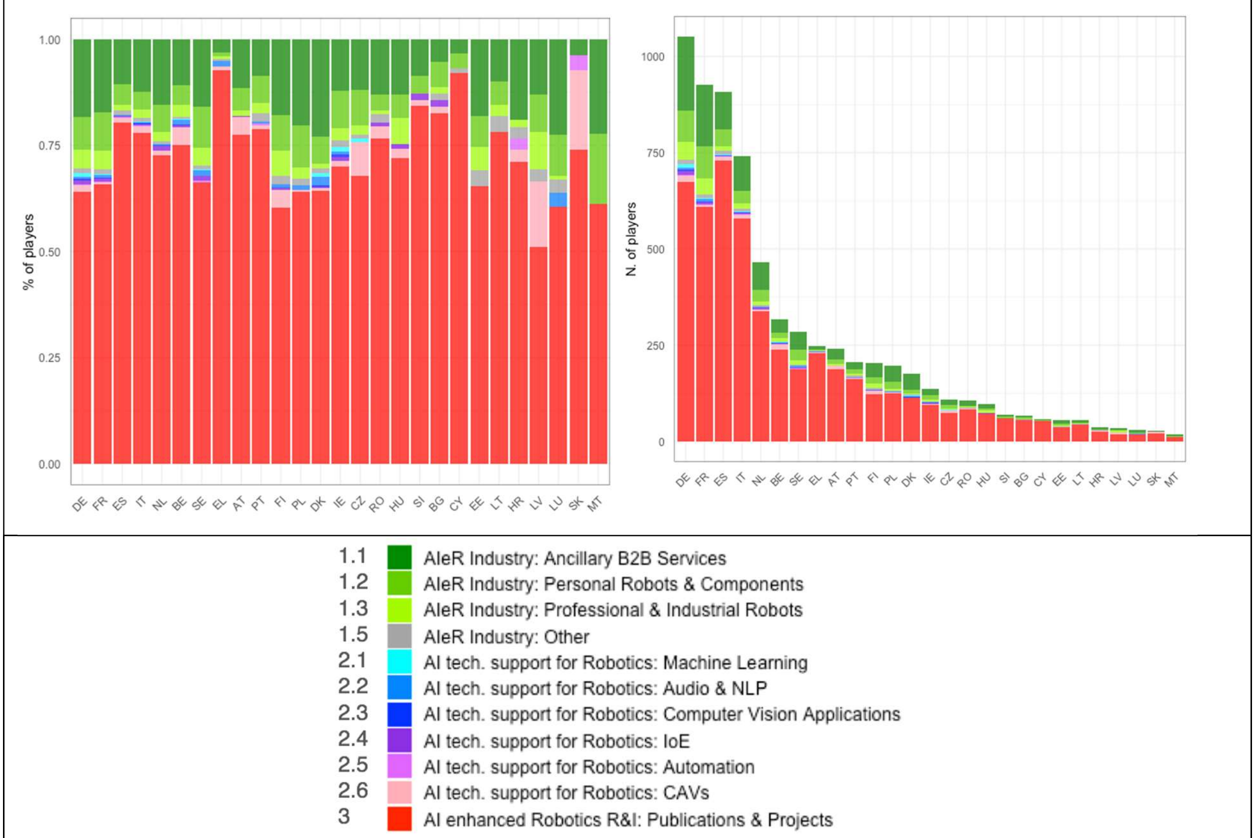
Finally, when looking at players involved in filing of patents, Germany is the country that stands out from the set. Although this finding cannot be used to assess the productivity (in terms of number patents) of the different national economic systems, it suggests a consolidated position of Germany in the AI for enhancing robotics landscape, as it is the only Member State with several players that are developing technological advancements in the domain.

Figure 14. AI for enhancing Robotics (AIeR) players by thematic area in EU27, in percentage terms and absolute values. EC-funded projects NOT included



Source: JRC elaboration

Figure 15. AI for enhancing Robotics (AIeR) players by thematic area in EU27, in percentage terms and absolute values. EC-funded projects included



Source: JRC elaboration

Figure 14 and Figure 15 present the number of AI players involved in AI for enhancing robotics by thematic area in percentage terms and absolute values, when EC projects are considered or not, respectively. It is possible to notice the very consistent boost that EC projects give to the most research oriented thematic area, "(3) AI for enhancing Robotics R&I: Publications & Projects". This is particularly evident for Spain, Italy, Greece, Austria and Portugal, as they all reach at least 75% of players involved in this thematic area when EC projects are considered (Figure 15). In general terms, all the Member States have more than 50% of players involved in "(3) AI for enhancing Robotics R&I: Publications & Projects" when EC-funded projects are considered.

When EC projects are not considered (Figure 14), no large differences are observable in terms of the percentage of players by thematic area among the top 4 countries, i.e., Germany, France, Spain and Italy. "(1.1) AIeR Industry: Ancillary B2B Services" is in general the thematic area including the largest portion of players, and it is followed by "(1.2) AIeR Industry: Personal Robots and Components" and "(1.3) AIeR Industry: Professional and Industrial Robots". Given the nature and complexity of the corresponding businesses, it is expected that the biggest part of players is in the provision of services and that the players producing and commercializing professional and industrial robots are fewer than those in the area of personal robots.

Poland is observed to be the only Member State (among those with at least 50 players in AIeR) with a percentage of players in "(1.2) AIeR Industry: Personal Robots and Components" exceeding 25%. For "(1.3) AIeR Industry: Professional and Industrial Robots" there is a significant involvement of players in Finland (15%), Belgium (11%), Sweden (10%), France (9%) and Germany (9%). Other Member States also present considerable percentages in this thematic area, including Hungary (25%), Latvia (25%), Estonia (16%) and Lithuania (13%). However, given the small number of players involved in AIeR (fewer than 25), these countries can at this stage only be considered relevant in terms of a possible future expansion.

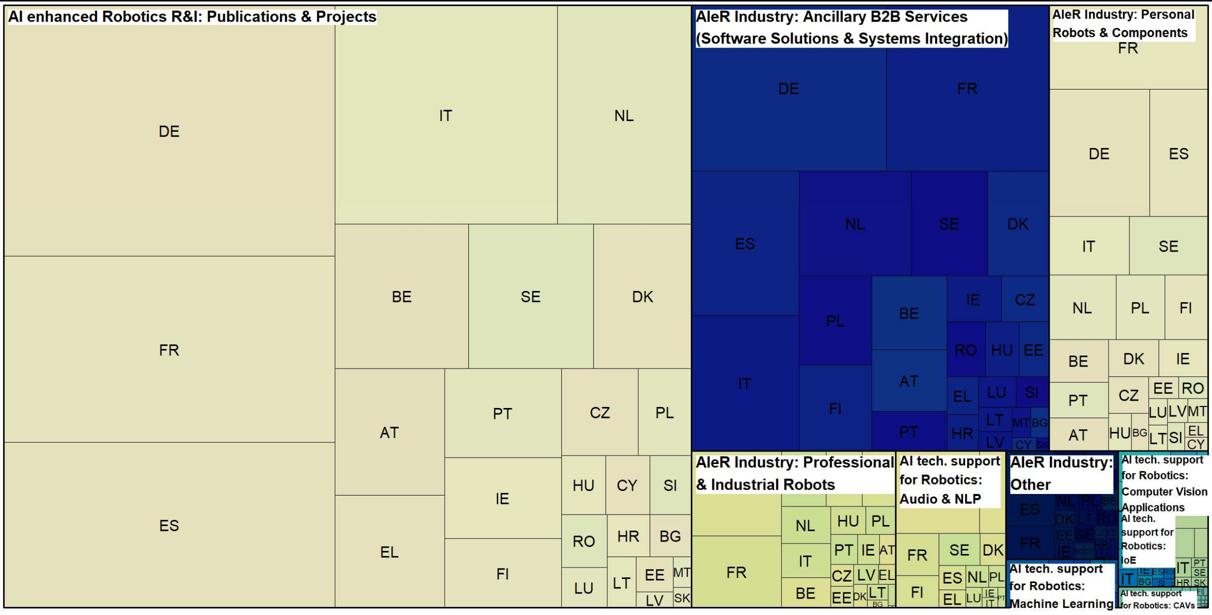
Some larger involvement in "(2.2) AI tech. support for Robotics: Audio & NLP" for Northern Europe countries such as Sweden and Denmark is noticeable, and there is also a remarkable percentage for Greece in this thematic area. We also notice some considerable percentages of players involved in "(2.4) AI tech. support for Robotics: IoE" for Bulgaria (8%), Slovenia (8%), Hungary (4%) and Romania (3%). Even if the overall number of players from each of these countries in AIeR is relatively small, it is interesting to observe their geographical proximity, which may indicate some specific industrial common pattern.

Once the effect of EC-funded projects is considered (Figure 15), apart from the expected boost in the thematic area of "(3) AI for enhancing Robotics R&I: Publications & Projects", it is possible to observe a significant involvement of players in "(2.6) AI tech. support for Robotics: CAVs" (light pink bars) in several countries, in particular Slovakia (19%), Latvia (15%), Czechia (8%), Austria (4%), Belgium (4%) and Finland (4%). This suggests that, especially for these countries, several H2020 and FP7 projects addressing the area of CAVs have implications in the domain of robotics, since their textual content revealed elements indicating their final inclusion in the AI for enhancing robotics landscape.

4.2 Thematic areas and Revealed Comparative Advantage (RCA)

Regarding the EU MSs, Germany, France, Spain and Italy are leading in several activities in most of the thematic areas. Belgium, the Netherlands, Austria, Denmark, Finland and Sweden almost always present a significant position in the ranking and their presence in the top-5 depends on the considered thematic area.

Figure 16. Number of AI for enhancing Robotics (AIeR) activities by thematic area and country



Notes: EU-funded projects are included.
Source: JRC elaboration

Figure 16 shows the number of activities per country in the EU27. Most of the EU27 MSs appear to be consistently active in the "(3) AI for enhancing Robotics R&I: Publications & Projects" subdomain. In fact, as we include the EU-funded projects in this stage of the analysis, this indicates the relevant contribution of EU on AI for enhancing robotics R&I.

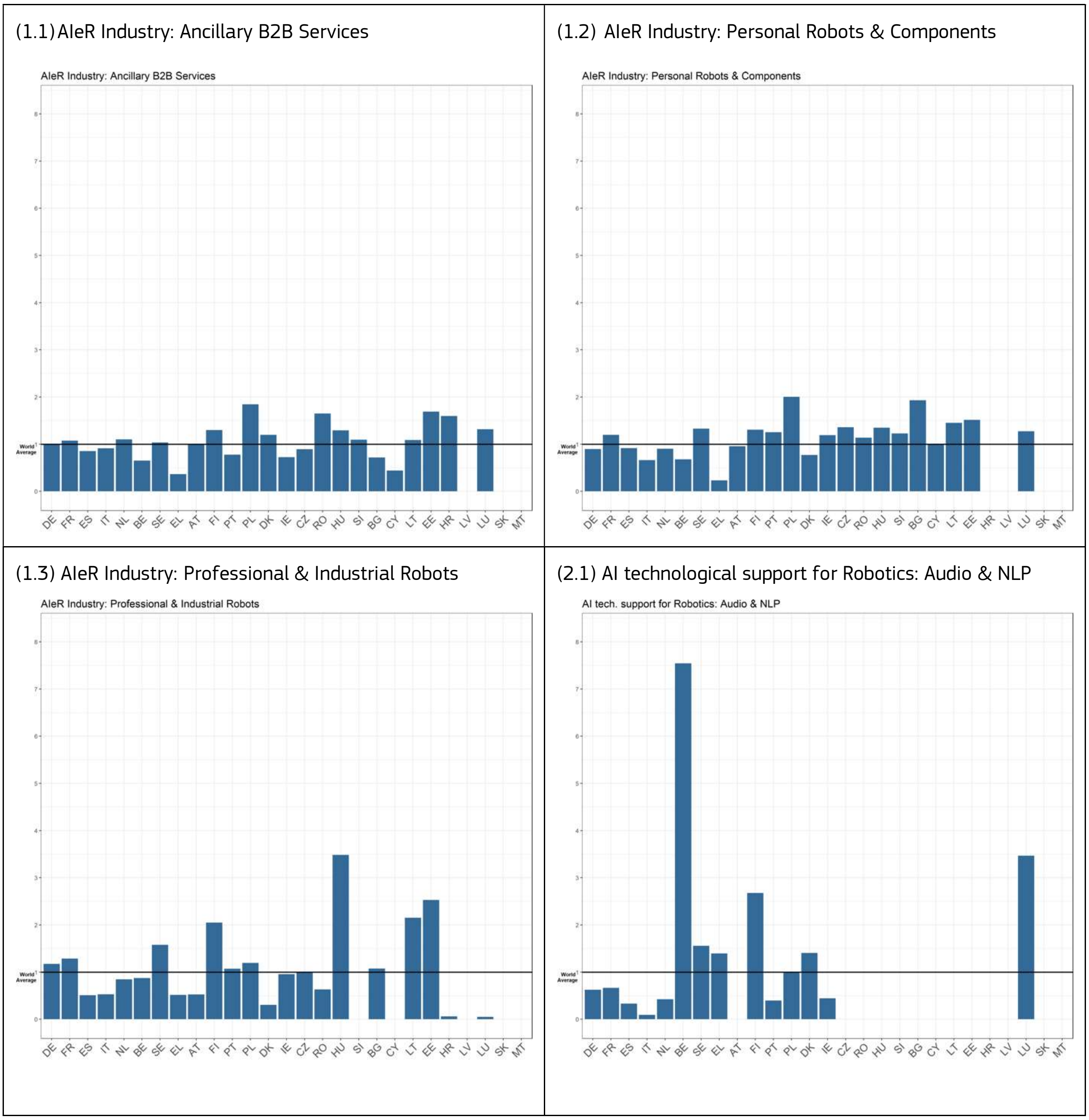
Regarding the part of the landscape more related to industry, in decreasing order we have "(1.1) AIeR Industry: Ancillary B2B Services", followed by "(1.2) AIeR Industry: Personal Robots & Components" and "(1.3) AIeR Industry: Professional & Industrial Robots". While the provision of services is easier to perform, the production and commercialisation of personal robots is more complex, in the sense that more resources and infrastructures are needed to assembly the final products. Thus, the production of professional and industrial robots is even more complex, given the size of these machines.

In the subdomain related to the "(2) AI tech. support for Robotics", we find that the most consistent number of activities is in the one about Audio & NLP (2.2). Other subdomains belonging to this part of the AIeR domain do not appear to contribute substantially, since the residual category (i.e., "(1.5) AIeR Industry: Other") appears to be the largest among them.

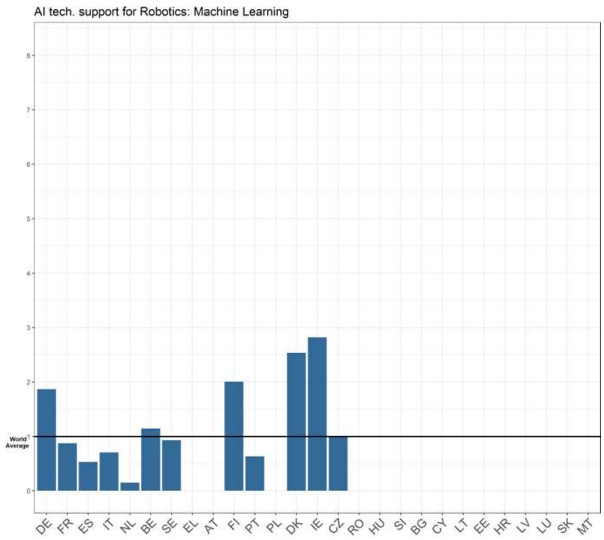
A preliminary note regarding the analysis of Member States' specialisation in the different thematic areas is important. Since in several cases some countries have a very limited number of activities in certain thematic areas, this would make the RCA indicator somewhat unreliable from an economic point of view (while still computable from a statistical point of view) and it would lead to misinterpretations of the same. Therefore, we do not report the RCA scores for the countries where less than 20 activities are detected. In Figure 17, the RCA of the EU Member States is presented for each thematic area of the AI for enhancing robotics landscape. We additionally recall that activities are considered in fractional counting. ([20])

([20]) In the case that an activity is perform, i.e., by two players from different MSs we assign 0.5 of the activity in the one country and 0.5 in the other one.

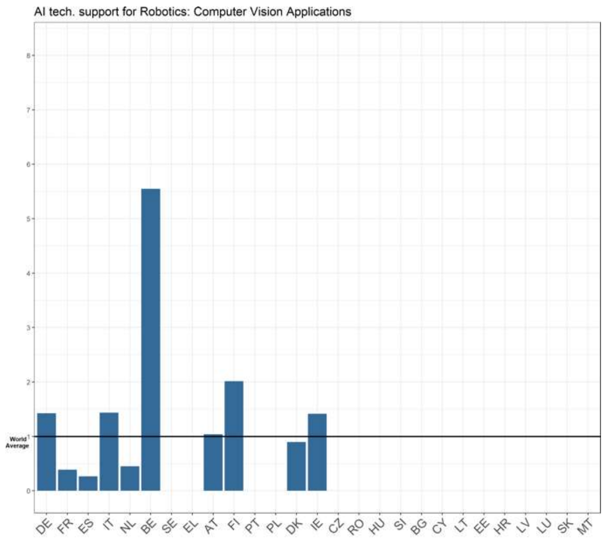
Figure 17. Revealed Comparative Advantage (RCA) by AI for enhancing Robotics (AIeR) thematic area worldwide (2009–2020)



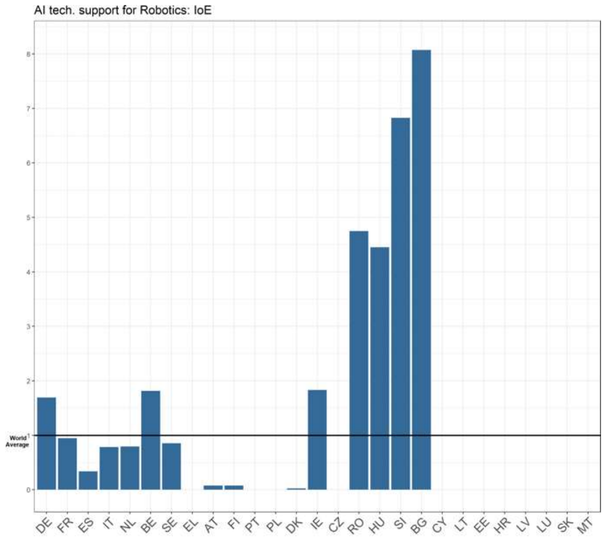
(2.2) AI technological support for Robotics: Machine Learning



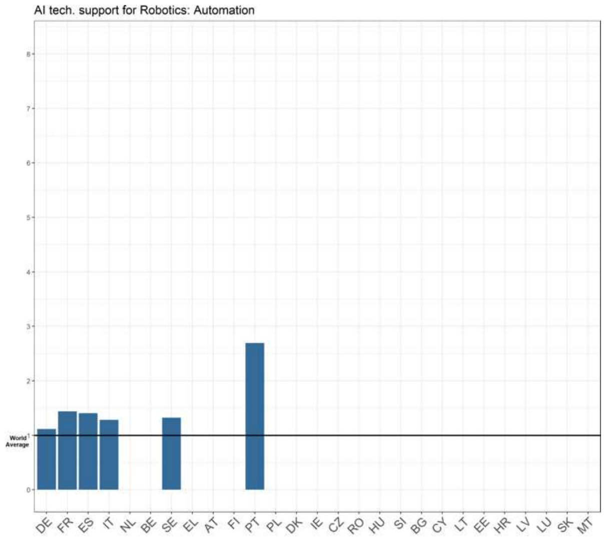
(2.3) AI technological support for Robotics: Computer Vision Applications

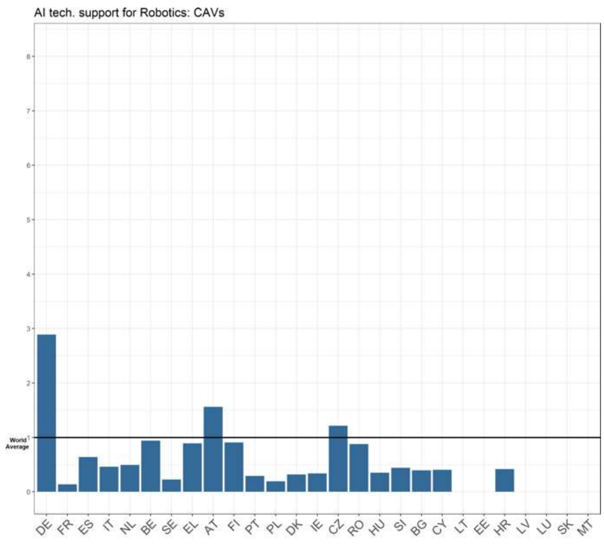
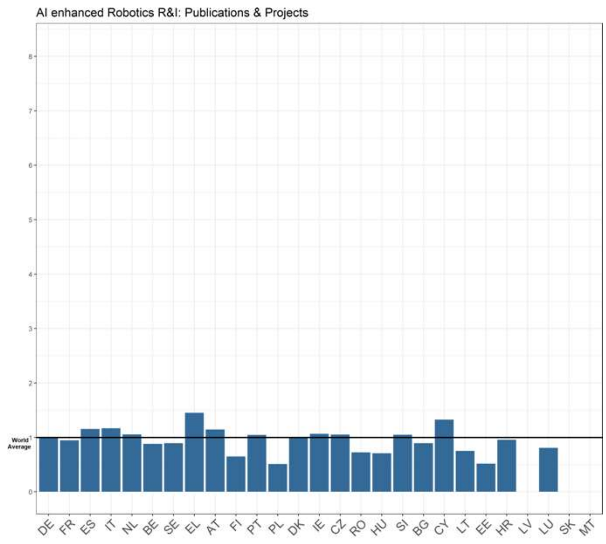


(2.4) AI technological support for Robotics: IoE



(2.5) AI technological support for Robotics: Automation



(2.6) AI technological support for Robotics: CAVs	(3) AIeR R&I: Publications & Projects
	

Notes:
(1) EU-funded projects are included.
(2) Thematic areas are presented considering the subparts of the AIeR landscape, in the same order as discussed in Section 2.2, and in decreasing order of number of activities that they include.
Source: JRC elaboration

It is not possible to observe strong specialisations in the “(3) AI for enhancing Robotics R&I: Publications & Projects” subdomain. In fact, all countries present an RCA which is close to 1 (the EU27 average). Greece is the only one presenting a considerably higher value, since 74 out of 90 total activities in Greece are within this thematic area (82%), which reveals a very good capacity to elaborate on sounding research projects that are finally selected to be funded. In general, the fact that this thematic area, which includes to a large extent H2020 and FP7, presents a uniform distribution is a positive signal in the sense that participations in EC-funded projects do not create imbalances among Member States.

The thematic area of “(1.1) AIeR Industry: Ancillary B2B Services” also presents a good balance among Member States, though some specialisation do emerge. In particular, Poland, Estonia, Romania and Croatia are revealed to have some good comparative advantages. In terms of total activities per country, we detected 39 out of 102 Polish activities in this thematic area (38.46%); 10 out of 28 (35.77%) for Estonia; 13 out of 38 (34.26%) for Romania; and 7 out of 21 (33.34%) for Croatia. Poland also appears to be the most specialised EU country in the thematic area of “(1.2) AIeR Industry: Personal Robots & Components”, this time along with Bulgaria (19 out of 102 activities for Poland, i.e., 18.63%, and 4 out of 22 for Bulgaria, i.e., 18.18%). To close the AIeR industry part, we observe a strong specialisation of Hungary in the thematic area of “(1.3) AIeR Industry: Professional & Industrial Robots” (6 out of 41 activities i.e., 14.63%). In the same thematic area, Estonia, Latvia, Finland and Sweden also present noteworthy specialisations. Even if Latvia and Estonia do not present a large number of activities, the overall findings suggest the presence of a geographic pattern regarding EU Northern-Baltic countries.

Activities related to the AI technological support for robotics thematic areas present some more evident specialisation. Although there are not that many AI for enhancing robotics-related activities in these thematic areas (226 in these 6 thematic areas, out of 4,239 total activities), the fact that we are able to identify these activities is still an added value, as it allows us to observe the overlap among the different topics of the whole AI landscape when specifically looking at AI for enhancing robotics. For the “(2) AI technological support for Robotics” subdomain, we report a remarkable specialisation of Finland and Luxemburg in “Audio & NLP”, a good RCA of Portugal in “automation”, and a considerable RCA of Germany in CAVs (which is expected given the size of German automotive sector). In addition, we observe that Belgium shows a good specialisation in “(2.3) Computer Vision applications” and in “(2.2) Audio & NLP”, and in both cases the presence of several continental and international organisations played a role in attracting players that are active in the field. These considerations smooth the large RCA observed in this case. In the “(2.1) AI technological support for Robotics: Machine Learning” thematic area, Ireland appears to be the most specialised country with an RCA score equal to 2.78, and Denmark holds the second position (RCA 2.42). Indeed, Ireland is considered an important European tech player as Dublin is considered among the most important cities of tech innovation with some of the most well-known players worldwide located there, including Apple, Google, Facebook and Amazon (Technology Ireland ICT, 2021). Germany and Finland also present considerable values in this thematic area. With "(2.4) AI technological support for Robotics: IoE" another geographical pattern is present, since Bulgaria, Slovenia, Romania and Hungary present large RCA values. This could be related to the recent shift of Central and Eastern European countries towards a more consistent use of robots in industrial processes (Reuters, 2018, 2020; Statista, 2021a).

Finally, we propose a closer look at the thematic area of "(3) AI for enhancing Robotics R&I: Publications & Projects". As this thematic area is sustained by a considerable number of EC-funded projects, we have provided two tables which describe the number of H2020 and FP7 by country and by priority. This makes it possible to gain some insights on the purposes for which the Member States took advantage of EC funds in the domain of AIeR. The projects are considered by means of fractional counting, i.e., the participation of a player in a project counts as 1 divided by the overall number of players in the project. We observe that, as expected, most of the EU countries used AIeR-related H2020 to pursue the "Excellent Science" objective. At the same time, a consistent group of countries (Spain, Greece, Portugal, Poland, Slovenia, Lithuania, Romania, Bulgaria and Croatia) mainly developed AIeR-related H2020 in the context of the "Industrial leadership" priority, which reveals a more economically-related use of EC funds. The only country mainly addressing the "Spreading Excellence and Widening Participation" is Latvia.

Concerning the FP7 program (2007–2013), projects were classified as reported in Table 3. ([21]) With respect of the EU AIeR landscape, few countries present a major involvement in the Specific Program "People", which was mainly supporting researcher mobility and career development. These countries are UK, the Czech Republic, and Poland (among those with at least five funded projects). Most of the Member States mainly used AIeR-related FP7 to create bridges between industry and academia, as addressed by the Specific Program "Cooperation". Nonetheless, there are some countries in which some more balanced distribution is observed. In particular, we notice that France was almost equally active in the three Specific Programs of "Cooperation", "Ideas" (supporting frontier research solely based on scientific excellence), and "People". This 360° approach to the AI for enhancing robotics domain is very structured and confirms the consistency of France in the domain. In addition, Spain shows a very balanced involvement between the Specific Programs "Cooperation" and "People", therefore combining efforts to create partnerships between industry and academia, with efforts in sustaining individual talents in research. Also, it appears this has a focused line of action, and it should not be a surprise that Spain is the third leading country in the domain.

([21]) See footnote 7.

Table 2. H2020 projects included in the "AIeR R&I: Publications & Projects", by project priority and country

N. of H2020 Projects in fractional counting based on participants	H2020 Priority 'Excellent science'	H2020 Priority 'Industrial leadership'	H2020 Priority 'Societal challenges'	H2020 Priority 'Spreading Excellence and Widening Participation'	H2020 Priority 'Science with and for Society'	Euratom	Sum by Country
UK*	161.2	46.4	23.7	1.8	0.8	0.3	**234.1**
ES	74.4	98.4	52.7	1.5	0.5	0.4	**227.8**
DE	125.5	71.3	27.2	2.7	0.4	0.6	**227.7**
FR	87.7	52.2	26.4	0.9	0.4	1.2	**168.8**
IT	67.6	57.0	27.1	1.8	0.5	0.2	**154.3**
NL	64.4	35.5	12.8	0.6	0.3	0.1	**113.6**
BE	31.2	15.4	14.1	-	0.3	0.2	**61.2**
DK	32.3	24.9	4.3	0.2	0.1	-	**61.8**
SE	24.4	24.5	10.1	0.7	-	0.1	**59.7**
EL	11.6	18.5	12.9	-	0.1	0.1	**43.3**
AT	17.7	15.6	8.7	-	0.6	0.1	**42.6**
IE	16.4	12.6	7.8	0.3	0.1	0.0	**37.1**
PT	7.9	15.4	10.8	1.2	-	0.0	**35.3**
FI	16.1	12.4	4.9	0.3	1.2	0.0	**34.9**
CZ	6.3	6.3	3.4	3.1	0.1	0.0	**19.3**
PL	4.1	7.6	6.7	0.5	0.1	-	**19.0**
CY	5.0	2.8	1.7	2.7	0.2	0.0	**12.4**
SI	1.9	5.6	2.2	0.6	-	0.1	**10.3**
LU	5.7	3.4	0.8	-	-	-	**9.9**
HU	4.3	3.7	1.8	-	-	0.1	**9.8**
LT	1.3	6.1	1.2	-	-	-	**8.7**
RO	1.2	3.4	2.3	0.3	-	-	**7.3**
EE	3.1	2.1	1.0	0.5	0.1	0.0	**6.8**
BG	1.7	3.0	1.2	0.3	0.1	-	**6.4**
HR	1.3	2.7	1.2	0.5	-	0.0	**5.7**
LV	0.1	0.5	1.5	-	-	-	**2.1**
MT	1.2	0.4	0.1	-	0.1	-	**1.7**
Sum by Priority	**775.8**	**548.1**	**268.8**	**20.4**	**6.1**	**3.5**	**1,622**

(*) Not part of EU27

Source: JRC elaboration

Table 3. FP7 Projects included in the "AIeR R&I: Publications & Projects", by specific programme and country

N. of FP7 Projects (in fractional counting) based on participants	FP7 Specific Programme 'Cooperation'	FP7 Specific Programme 'Ideas'	FP7 Specific Programme 'People'	FP7 Specific Programme 'Capacities'	Sum by Country
UK*	39.5	27.0	53.1	4.4	**124.0**
DE	52.3	15.5	24.8	3.6	**96.2**
FR	26.7	23.5	20.1	1.1	**71.4**
IT	40.1	9.5	14.4	3.5	**67.5**
ES	28.8	2.0	27.1	7.0	**65.0**
NL	17.5	6.0	11.6	2.4	**37.6**
EL	11.7	0.5	7.4	2.2	**21.8**
BE	8.7	7.0	3.9	1.4	**21.0**
AT	10.3	3.5	4.4	0.8	**18.9**
SE	9.4	6.0	2.7	0.3	**18.4**
PT	6.7	-	4.6	1.9	**13.1**
IE	4.1	1.5	3.6	0.5	**9.6**
DK	5.0	2.0	1.9	0.6	**9.5**
CZ	3.2	1.0	4.2	0.6	**9.1**
FI	3.6	1.0	2.0	0.9	**7.4**
PL	2.4	-	3.6	0.3	**6.4**
HU	2.1	2.0	-	0.6	**4.8**
HR	1.0	-	1.2	2.5	**4.7**
RO	1.7	-	0.3	2.5	**4.6**
SI	3.7	-	0.3	0.2	**4.1**
BG	0.9	-	1.2	1.3	**3.4**
CY	0.8	-	0.6	0.9	**2.3**
MT	0.1	-	1.0	0.6	**1.7**
SK	0.1	-	0.7	0.4	**1.2**
EE	0.7	-	0.1	0.3	**1.2**
LV	0.5	-	-	0.0	**0.5**
LT	0.4	-	-	0.0	**0.5**
Sum by Priority	**282.4**	**108.0**	**194.7**	**40.8**	**626.0**

(*) Not part of EU27

Participation to projects has been computed in fractional counting based on the number of participants in each consortia.

Source: JRC elaboration

5 Conclusions

This report provides insights on the composition and status of the worldwide AI for enhancing robotics landscape, with a specific focus on the EU. It thereby aims to support to policymakers in the context of the EU twin green and digital policy priority, as AI for enhancing robotics is a key area to this twin transition.

The report analyses the intersection between AI and robotics, by exploring the presence of activities related to robotics within the AI-related activities identified in the global AI landscape (Samoili et al., 2020; Righi et al., 2020). The resulting AI for enhancing robotics domain is mapped and explored in those subdomains and thematic areas which emerge when applying the TES methodology and results. Based on tech-mining techniques, we detect economic players (firms, research institutes and governmental institutions) active in the AI for enhancing robotics global landscape, identifying not only AI players directly involved in core "autonomous robotics", but also producing or commercialising products and services related to AI for enhancing robotics, or AI based software robots.

As a result of a bottom-to-top exercise with a supply-side perspective, we identify three main subdomains, in decreasing order of closeness to market: "(1) AI for enhancing Robotics Industry", "(2) AI technological support for Robotics", and "(3) AI for enhancing Robotics Research & Innovation: Publications and Projects". The presence of ancillary B2B services integrating AI for enhancing robots in already existing economic activities is also emerging.

As the approach used in this report considers R&D and production rather than adoption of robotics, it has the key benefit of allowing monitoring actual economic activities in this domain. It targets economic players involved in the production, commercialisation and research, while most current specialised reports only concern the adoption of robots. This original perspective can be adopted thanks to the possibility of exploring the micro data of the AI TES landscape. This approach can therefore provide an overview on the entire global landscape, as well as a more detailed focus on the landscape in the EU27 Member States.

The report findings confirm that the US, China and the EU27 are leading in the AI for enhancing robotics global ecosystem. The report results show that:

- In the **US**, the AI for enhancing robotics landscape accounts for 30% of the US AI players. Furthermore, the US players in the AI for enhancing robotics landscape represent 32% of all the AI for enhancing robotics players worldwide.

- In **China**, the AI for enhancing robotics landscape accounts for 27% of the Chinese AI players; their involvement is more related to the automation area, in which China is a leader.

- In the EU27, the AI for enhancing robotics landscape accounts for 33% of the EU27 AI players.

- The UK percentage (25%) of AI for enhancing robotic players (out of the total number of AI players) is 8% lower than the one of EU. Hence, from the perspective of AI for enhancing robotics, the departure of the UK from the European Union should be of somewhat less concern for the EU than when considering the whole AI landscape (in which the UK is a key country). In absolute numbers, the UK does have a high number of players in AI for enhancing robotics, although, this is not a characteristic specific to AI for enhancing robotics, but rather a general point regarding the UK and the whole AI field, meaning that the UK players are quite active in the AI field.

- In Japan, one of the top countries worldwide in robotics, the AI for enhancing robotics landscape also accounts for 30% of players in the AI landscape. This attests, an important synergy between AI and robotics. In addition, a strong specialisation in "(2.6) AI technological support for Robotics: CAVs" is found, due to the direct connections between AI for enhancing robotics players and the Japanese automotive industry. Key Japanese players in robotics are Honda (producing ASIMO, which is considered the most advanced humanoid robot), Kawasaki, Yamaha, and Denso. In addition, Japanese players are also consistently involved in "(3) AI for enhancing Robotics R&I: Publications and Projects".

- South Korea is currently considered the "most robotised economy" in the world, but it does not yet appear to be deeply involved in the production of AI for enhancing robots. Nevertheless, the important presence of national players in "AI tech. support for Robotics: (2.1) Machine Learning, (2.2) Audio & NLP, (2.3) Computer Vision Applications, and (2.4) IoE", confirms the presence of the large South Korean high-tech companies (e.g., Samsung, LG) in the development of electronic devices and components used in robotics. Considering the strong know-how in AI that these large high-tech groups have recently accumulated, such a combination is likely to be the premise of a more important future production of AI for enhancing robots. In addition, we also observe a considerable involvement of the automotive sector in AI for enhancing robotics players (with players like Hyundai Robotics), in a similar way to Japan.

- The EU has an important specialisation in most of the thematic areas. Higher activity or RCA are observed in "(1) AI for enhancing Robotics Industry" areas (i.e., "(2.1) Ancillary B2B Services", "(2.2) Personal Robots & Components", "(2.3) Professional & Industrial Robots") and in "(3) AI for enhancing Robotics R&I Publications & Projects". The fact that the EU has a comparative advantage in the most research and innovation oriented thematic areas suggests a favourable positioning in terms of future innovativeness and competitiveness.

- When considering EU Member States individually, the four leading countries in the AI for enhancing robotics landscape in terms of number of players are Germany, France, Spain and Italy. Next, Belgium, the Netherlands, Austria, Denmark, Finland and Sweden have a strong position in the ranking, depending on the thematic area considered.

- Regarding the different categories of players, Germany and France have at least twice the number of industrial players found in any other Member States, indicating a more mature economic stage. These two countries also have a large number of players producing frontier research publications, which suggests a good balance between research and industry. Although Spain and Italy do not have many players involved in AI for enhancing robotics as compared with Germany and France, they nonetheless have a balanced presence of research institutions and firms. Since this balance remains basically unaltered when considering the effect of EU-funded projects, this situation is likely to favour stable connections between industry and research, which in turn can sustain higher innovativeness and competitiveness.

- Considering the specialisation of EU Member States:

    - In general terms a strong impact of EU-funded projects is observed, since all the Member States have more than 50% of players involved in the thematic area of "(3) AI for enhancing Robotics R&I: Publications & Projects". The results also show a strong specialisation of Greece in this category. As EU projects strongly affect this thematic area, this strong specialisation shows a reliance of players in Greece on elaborate sound research projects that are eventually selected to be funded. Except for Greece, the results do not show a strong specialisation of other Member States in this category. This may also be interpreted as positive, in the sense that participations in EU-funded projects do not create unbalances within Member States.

    - The results show specialisation in Poland, Estonia, Romania and Croatia in the category "(1.1) AIeR Industry: Ancillary B2B Services". While in the category "(1.3) AIeR Industry: Professional & Industrial Robots", the most specialised countries are EU Northern-Baltic countries: Estonia, Latvia, Finland and Sweden.

    - Finally, results show a strong activity of Spain in terms of EU-funded projects. First, Spain had a considerable number of projects in the FP7 Specific Programs "Cooperation" and "People", therefore combining partnerships between industry and academia, with support to individual talents in research. Then, Spain has also experienced a large number of Horizon 2020 projects under the priority "Industrial leadership". It therefore appears that Spain has been able to implement a focused line of action directed at fostering the AI for enhancing robotics industry.

Overall, this study analyses the AIeR domain, structured in terms of the landscape's main subdomains and, within them, the AIeR thematic areas. In fact, the analysis conducted refers to a snapshot of the most recent developments in the field in order to monitor them and identify potential characterisation. Indeed, robotics technology is experiencing a strong evolutionary period. This study explores a subject (i.e., "AI for enhancing robotics") which is currently on the edge of first large-scale commercialisation, meaning that what is considered is a recently emerged techno-economic area. Thus, the analysis of trends is not expected to provide very interesting insights, as it will be hard to capture the evolution of a domain whose development has only just started. In this respect, it is deemed more scientifically sound the investigation of the overall thematic structure of AIeR subdomains.

Indeed, further research is advisable to deepen the analysis of the complex landscape presented in this report. Potential further analyses might focus for example on: (i) the consideration of more specific characteristics of the AI for enhancing robotics firms, e.g., size, sector; (ii) exploration of the geography of venture capital in AI for enhancing robotic; (iii) network analysis of national and international collaborations, strategic position of players and geographical areas; and (iv) impact assessment to explore the effect of EU-funded projects (H2020/FP7) on the European economy more deeply.

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List of abbreviations and definitions

AI	Artificial Intelligence
AIeR	AI for enhancing Robotics
CAVs	Connected and Automated Vehicles
CV	Computer Vision
EC	European Commission
EU	European Union
IoE	Internet of Everything
IoT	Internet of Things
ML	Machine Learning
MS	Member State
NLP	Natural Language Processing
R&D	Research and Development
R&I	Research and Innovation
TES	Techno-Economic Segment analytical approach

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The European Commission's science and knowledge service

Joint Research Centre

JRC Mission

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