Innovate UK

# THE UK RAS LANDSCAPE:

## UK capability in Robotics and Autonomous Systems over the coming decade

**Report Commissioned by Innovate UK**

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UNIVERSITY OF CAMBRIDGE
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IfM Engage

# Executive summary

This report commissioned[1] in early 2022 by Innovate UK, presents the results of work to collaboratively engage a wide range of industrial and other key stakeholders in developing a view of the service robotics[2] supply chain in the UK. This encompasses both RAI (robotics and artificial intelligence) and RAS (robotics and autonomous systems)[3]. The report aims to be a snapshot for the UK service robotics sector and broader stakeholder communities concerning the vision and potential evolution of the industry supply chain out to 2032 and beyond.

The report sets out a vision for service robotics from the perspective of end users and supply chain stakeholders and identifies strengths and weaknesses in the current UK position with respect to robotics. It identifies key areas such as skills, cross sector regulation, SME support and funding that need to be systematically and strategically addressed to create the long-term momentum required to meet the opportunities robotics offers the UK. The report also sets out, from the perspective of the participants the likely future projection of robotics impact within sectors and highlights key value creation opportunities for robotics supply chains and end users in six specific areas. In each of these areas there was consensus that the realisation of these opportunities for the UK was feasible, that the capability to achieve them was available and that wide scale adoption could be achieved with concerted investment by government and industry.

The report also makes a series of recommendations that are designed to stimulate the UK supply chain and enhance awareness in end user organisations of the benefits of robotics in general. In particular it identifies the need to create cross sector networks and increase coordination among stakeholders, develop innovation-enabling regulation around emerging technologies and develop wider skills programmes at all educational levels and within industry, to drive up capabilities and awareness.

Finally, it identifies the need for sustained long-term funding to support the acceleration of research and its translation, the scale-up of innovative companies and the stimulation of uptake in industry and public service organisations.

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1 From University of Cambridge Institute for Manufacturing

2 See https://ifr.org/service-robots and also appendix 1 for the corresponding definition by the International Organization for Standardization (ISO 8373).

3 In general, these can be classified as 'advanced robotics', since they can interact with their environments and can move either themselves or their manipulators/end effectors, having either a meaningful degree of 'autonomy' and/or the ability to use sensors to carry out sophisticated surveillance and data collection.

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# 1 Introduction, objectives and scope

## 1.1 Report purpose

This report presents the results of work commissioned by Innovate UK (IUK) drawing on expertise in UK industry to develop a snapshot of UK service robotics, encompassing RAI (robotics and artificial intelligence) and RAS (robotics and autonomous systems) and to provide guidance on the key steps the UK needs to take in order to encourage growth and uptake.

The report elaborates the vision from a supply chain and ecosystem perspective looking towards the end users within sectors and elaborates a "pull" rather than "push" viewpoint. It therefore aims to:

- Synthesise a consolidated vision for smart machines that can stimulate the UK service robotics stakeholders' strategic thinking towards a vision for a stronger and more globally competitive UK service robotics sector over a ten-year window.
- Provide a set of recommendations enable the UK service robotics sector's ten-year vision to focus on developing and enhancing the UK's end user supply chain.
- Identify UK specific capabilities that are essential for the transformation of industry, both now and in the medium to long term by providing a broad landscape of the robotics sector's breadth of related technologies, thematic content, and activities.
- Stimulate cross sector opportunity between market segments[4] where the service robotics sector's technologies and innovations have an enabling or underpinning role.
- Allow policy makers, decision-makers[5] and organisations tasked with implementation of smart machines The means to identify, evaluate and select among strategic alternatives for achieving the vision and objectives.

The report also aims to improve the understanding of end users in what service robotics services and capabilities can offer and to disseminate key messages about smart robotics to second tier suppliers.

## 1.2 Report overview

The report is written based on a consolidation of the wide range of material gathered from the workshops undertaken during 2022, through a process described in Appendix 2.

It is divided into sections starting with a broad introduction to robotics and the vision for the UK supply chain both from the perspective of the end users and robotics supply chain and identifying key trends, drivers, enablers and barriers. This is followed by an analysis of the strengths and weaknesses in the UK and globally for robotics. The

[4] For example, in agriculture, construction, logistics, transport, etc.,

[5] From HM Government, devolved or local governments as well as regulatory and funding agencies/organisations.

report then examines in some detail the likely progression over time of robotics and presents value creation opportunities that exist within the UK.

Finally, the report offers recommendations on the support and approach needed to stimulate the supply chain by enabling the end user market and how to ensure that UK companies are well placed to deliver against end user needs and global demand.

The two Appendices detail the underlying methodology and approach to the work and detail the process undertaken during the workshops to create the various viewpoints documented here.

**Note**: that in places throughout the text direct quotes are included from the materials collected during the interactive sessions that provided the raw material for this document. They are displayed as indented paragraphs as follows:

> *'Key components and algorithms will expand capabilities and open new market opportunities.'*

# Robotics Background

Robotics is an inherently interdisciplinary field dealing with the design, construction, operation, and use of robots, thus bringing together diverse scientific disciplines (e.g., engineering, computer science, social sciences, humanities) with many actors and stakeholders, each with different perspectives and interests.

Robots are today primarily deployed in the manufacturing sector in highly controlled and scalable environments, configured for specific tasks necessary for volume manufacturing. These robots are considered as having a low-level of intelligence, with the majority of them requiring manual reconfiguration for task or environmental adaptations.

In the last decade it has become possible to embed greater sensing and interpretation capability into robotics systems leading to improved decision making and physical action. As a consequence, robots that can operate in dynamic, unstructured environments have been developed and new markets have opened. For example, in teleoperated surgical tools, in farming (smart tractors), in inspection and maintenance tasks (drones) and in specialised manufacturing processes (cobots).

These advanced robotic systems can also be deployed to operate “autonomously” in environments which are highly structured, like, for example, in specific types of highly compartmentalised warehousing.

The increase in AI capabilities means that the level of intelligence that can be commercially deployed is increasing and, as it does so, new application areas will open across a multitude of sectors. This shift is characterised by a rise in the number of service, rather than manufacturing, applications that robots are applied to.

This is highlighted by the BEIS research paper ‘*The economic impact of robotics & autonomous systems across UK sectors*’ published in 2021 estimates the potential UK GVA uplift could be £150 Billion by 2035[6]. This estimation is based on the UK deploying best in class robotics across a variety of sectors[7]. Critically, the same report indicates that if we fail to fully adopt robotics and continue to progress at our current rate of deployment we will only reach some £6 billion of uplift. This would not only be a failure to seize the initiative but a failure to capitalise on our technical and research strengths.

From an end user - viewpoint the deployment and adoption of service robotics will significantly alter the underlying tasks in those sectors and will change the nature of jobs. Robotics has the capability to transform operations in most sectors, drive new business models, and unlock new means of value generation. The degree of impact will differ between application areas and market segments and over time depending on the readiness of an organisation/ sector/ segment to innovate. Other factors influencing uptake are the financial and technical readiness to deploy, the nature of tasks being automated and the engagement and acceptance of the workforce, management and users. These uptake factors point to the need for a broad spread approach to national capability building that adopts an appropriate balance between technology development and support for deployment and uptake by end users.

6 See ‘The economic impact of robotics & autonomous systems across UK sectors’, BEIS, 2021.
7 The sectors addressed are Agriculture, Construction, Food and Drink services, Health and Social Care, Energy and Infrastructure; industrial manufacturing is not included.

*'…educating people about the possibilities of robots and their ability to support them. There is currently a skewed view of robotics and automation, lacking personal experiences and with no grasp of what robotics can do. People need to be engaged to build trust.'*

## 1.3 Robot categories & applications

There are different definitions and segmentations/categorizations for robots which are commonly used, but they are in general very broad and when looked upon more closely are not always identical.

Towards a better standardization, various organisations, committees etc. have worked to develop definitions and segmentations/categorizations/ontologies that can be applicable for all of the robot types. Representative examples include the International Organization for Standardization (ISO) expert committee[8], the International Federation of Robotics (IFR)[9] and the IEEE RAS (Robotics and Automation Society)[10] which has undertaken the task of unifying the various ontologies consistently.

The ISO 8373:2012 standard defines the robot as:

- ***Robot:*** *programmed actuated mechanism with a degree of autonomy to perform locomotion, manipulation or positioning.*
    - *A robot includes the control system.*
    - *Examples of mechanical structure of robots are manipulator mobile platform and wearable robot.*

While this is the most commonly used definition of a robot, we must note that:

- it refers exclusively to Cyber-Physical systems, thus excluding software only systems (i.e. software bots like chatbots).
- It implicitly excludes stationary robots.
- as it requires a degree of autonomy[11] it excludes systems that do not receive any feedback from their environments, or those that are remotely controlled.
- In the same standard medical robots are not regarded as either industrial or service robots.

Furthermore, while IFR does adopt the ISO definition, it further clarifies that autonomous cars are not considered robots, and thus are excluded from its analyses.

In this report, a robot or robotic system is seen as a system-of-systems (SoS) created by heterogeneous collections of physical and information resources joined together

[8] https://www.iso.org/obp/ui/#iso:std:iso:8373:ed-3:v1:en
[9] https://ifr.org/
[10] https://www.ieee-ras.org/
[11] Autonomy is defined ability to perform intended tasks based on current state and sensing, without human intervention.

by intricate physical or logical connections and interactions. As the term implies, an SoS consists of components that are themselves systems.[12]

At a high level the following categories are commonly used to classify robots:

- Conventional vs advanced robots[13]
- Industrial[14] vs Service robots[15] [16]
- Professional vs personal robots[17]

The ISO 8373:2012 standard defines the Service robot as:

- **Service robot***: robot in personal use or professional use that performs useful tasks for humans or equipment.*[18]
  - *Tasks in personal use include handling or serving of items, transportation, physical support, providing guidance or information, grooming, cooking and food handling, and cleaning.*
  - *Tasks in professional use include inspection, surveillance, handling of items, person transportation, providing guidance or information, cooking and food handling, and cleaning.*

While this is the most commonly used definition, we must note that it is based mostly on sector of application type or on the nature of the tasks that the robots are to perform, with minimal technology focus. Working along the same lines, the (non-mutually exclusive) categories that considered here are:

- Field Robots: non-factory mobile robots that operate in dynamic, unstructured environments.
  1. Based on Application domain
     - Agriculture
     - Logistics (both manufacturing and non-manufacturing)
     - Cleaning (professional & personal)
     - Construction and Demolition
     - Rescue and Security
     - Inspection and Maintenance
     - Defence
  2. Based on environment of operation

[12] Formally, the term can be used if its components have (at least in part) operational and managerial independence; sensing, mobility/locomotion, manipulation, energy/power, communication, autonomy engine, human-machine-interface, and high-level decision/control systems are joined together for a robotic system-of-systems. A multi-robot-system or a swarm increases further the overall system complexity.
[13] The boundaries between them are changing, and no widely accepted definition currently exists. In general, a robot is considered as advanced if it is capable of taking commands and reacting to them or interacting with the real-world environment's conditions to operate & solve real-world problems.
[14] For details on the definition of Industrial robots see Appendix 1
[15] Industrial robots are usually considered to be conventional robots, but this is not always the case; Industry 4.0, includes advanced robots used in manufacturing facilities that can operate without human supervision. Service robots are usually classified as advanced.
[16] According to the IFR there are roughly 5 times more service robots than industrial robots suppliers.
[17] This distinction is usually addressing service robots.
[18] Various taxonomies for Human–Robot Interaction (HRI) and related classifications also exist.

- Extreme/Harsh Environments
- Space Robotics (commercial & defence)
- Marine Robotics (including Underwater - commercial & defence))
- Aerial Robotics (commercial & defence)

3. UxVs[19] (including fully autonomous vehicles – commercial & defence)

- Laboratory
- Healthcare & Medical
- Socially Intelligent/Human Interaction based
  - Public Relation Robots (professional)
  - Personal/Domestic
    - Robot Companions for Assisted Living
    - Entertainment Robots
    - Elderly and Handicap Assistance

Further segmentations based on various characteristics of service robots also exist, like, for example bio-Inspired, miniaturised, wearable, exoskeletons, collaborative, swarms, etc.

## 1.4 Scope

The framework for this work considers the 'value chain/constellation' view[20] of the service robotics shown in **Error! Reference source not found.**, which includes the various roles that related organisations can have/play.

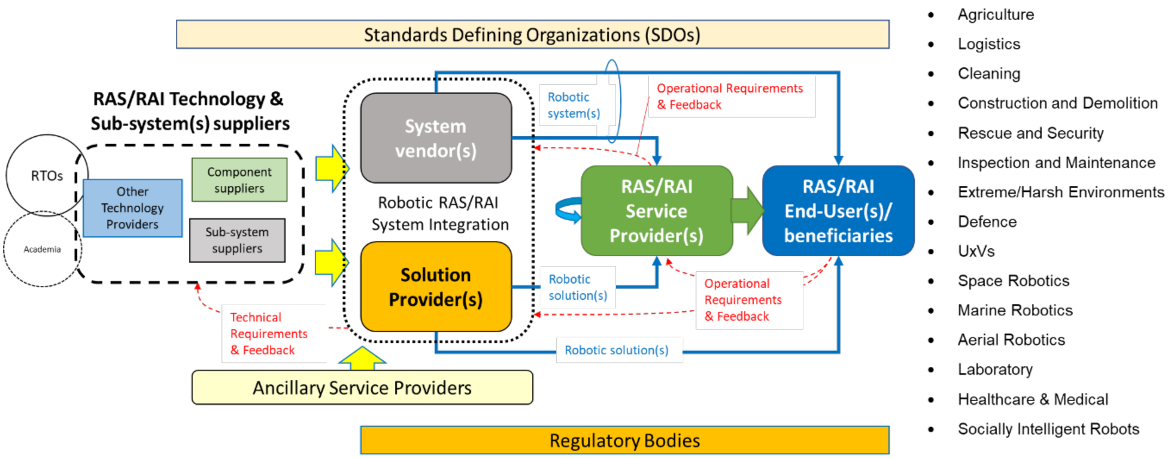


**Figure 1: Service robotics value constellation Source: Innovate UK.**

Taking a more holistic perspective this values constellation depicts the more complex, symbiotic transactional links among the multiple participants, each of which may create and consume value, moving away from the binary buyer-seller value chain.

The intent is not to capture only the buyer-seller value chain, but to include the other value contributors in the service robot domain. The main reason for this is that

[19] UxV: Uncrewed ground/aerial/surface/underwater Vessel/vehicle.
[20] Supplied by Innovate UK.

considerable value in a robotics system (or System-of-Systems) can be from other than the supplier/system vendor role, and this should be taken into consideration, in particular for the service robotics market.

In this work the perspective taken is from the UK's 'upstream' value constellation looking towards both the UK's and rest-of-the-world end users/beneficiaries and associated application/market areas.

## 1.5 Global context

In this section a global context perspective is provided for service robots based mostly on the key related points of IFR's World Robotics 2023.[21]

The service robot industry is more diverse and less tangible than the industrial robot industry. The IFR's Statistical Department is currently aware of 975 service robot system vendors worldwide. This excludes prototyping services and system integrators/solution providers. Many companies are still in the funding or prototyping stage and intend to offer a marketable product in the future.

- Field robots are becoming popular in agricultural/farming applications; key drivers for this trend include the shortage of skilled workers and environmental challenges.
    - For these robots to work completely in autonomous mode is harder than initially anticipated.
- Service robots are seen as a means to combat the lack of trained workers. In 2022 the number of new professional service robots sold went up by 48% (almost 158,000 units) compared to a 12% decline in consumer service robots.
- The size of the RaaS fleet grew by 50% to more than 21,000 units & RaaS business models enjoy growing popularity:

Top 5 application areas for professional service robots are:

1. Transportation & Logistics
2. Hospitality
3. Medical & Healthcare
4. Professional Cleaning
5. Agriculture

[21] IFR World Robotics 2023, September 2023

# Summary of outputs

This summary begins with the visions and perspectives from the robotics supply chain and their end user customer base. It examines general drivers, enablers and barriers to growth and uses the workshop input to relate the progression of robotics over the next decade and the expected value creation opportunities.

## 1.6 Visions and perspectives

The participants in the collaborative process consider there to be significant upside to greater deployment of robotics. this is echoed more generally in the robotics industry and in a variety of external assessments[22][23] As pointed out above this is a viewpoint that is also backed up with an independent assessment of the economic impact.

The primary economic impact from robotics occurs when they are deployed within end user sectors, so GVA impact is driven by uptake and strong uptake requires well developed supply chains that are aligned to the needs of the end users. This includes the provision of services that configure and maintain systems against the specific needs of each sector. While there will be opportunities for cross sector supply, and the use of common methods, robotics enabled services and system suppliers are likely to be sector focused. Impact is therefore dependent on the stimulation of a well founded robotics supply chain.

In addition, to ensure the supply chain can "pull through" innovation the pipeline between technology based innovators and companies in the supply chain needs to be reinforced. This involves streamlining the assessment of new technical innovations, within end user contexts, their incorporation into services, systems and processes and the testing and validation infrastructure needed to certify operation.

The following sub-sections, summarise the ten-year vision perspectives of two stakeholder groups; the end user beneficiaries and the UK's service robotics industry.

### Service robotics end user beneficiary vision

The national vision for the service robotics market in 2032 and beyond is that all relevant business organisations will have grasped the importance of robotics in their specific context and used it to significantly raise competitiveness.

From the perspective of end users, the beneficiaries of the technology, they will expect, by 2032 to be able to access;

- a well founded supply chain in the UK able to pull through innovation from within the UK and globally,
- a body of knowledge on the applicability and deployment of robotics and of the payback on investment,
- a well established and reliable, nationally accessible robotics infrastructure, a qualified workforce and network of providers.

22 https://www.pwc.co.uk/economic-services/assets/international-impact-of-automation-feb-2018.pdf
23 https://www.the-mtc.org/media/vevauetq/automation-and-robotics-research-paper-a4-pages.pdf

**To reach this point** end users call for organisations providing robotic systems or services to;

- articulate the potential uses and usability of robots for the operational needs of end users;
- demonstrate the value proposition sector by sector and application by application, including the impact and benefits of adoption, providing sector relevant economic data and appropriate technical "fit" to need; and
- provide the necessary systems integration services that are tailored to the needs of each sector, including supporting any regulatory needs or uncertainties.
- help them overcome current barriers to adoption of robots, for example anxieties that robotics will displace an existing workforce rather than enhance how it operates.

In addition, end users call for public agencies to champion and stimulate public sector uptake and innovation, including through taxation and private investment relief, that ease the introduction of robots into end user operations.

## UK's service robotics industry vision statement

The national vision for the UK robotic ecosystem includes global leaders and vendors being present in the UK stock market; it will maximise the use of UK design, innovation, manufacturing, and deployment skills; and will be capable of fulfilling the majority of the UK's robotics uptake across the different sectors.

The post-2032 vision of the UK's service robotics industry is to have;

- a mature UK robotics innovation ecosystem;
- a regulatory landscape conducive to innovation;
- a complete supply chain that meets end user needs; and
- UK based organisations competing successfully on a global scale for the supply of robotics technologies, systems and services.

**To reach this point** the sector calls for end user organisations, including public agencies, to:

- Proactively drive robotics uptake, examine how to deliver new robotics enabled service models within their sector that improve productivity or deliver against safety and environmental targets.
- Work with the robotics supply chain to understand business need and deployment progression.
- Create awareness within their organisations of the benefits and risks of robotics and ensure this reaches decision makers at all levels in their organisation.
- Work with regulators to provide a landscape that enables robotics innovation and pull through.
- Invest in training and skills appropriate for the use of robotics within their sector.

These actions need to be taken together as a combined strategy driven by sector champions. With sufficient momentum cross sector benefits of scale will emerge including around common regulation and supply standards. Public engagement in co-creating the ecosystem that connects these stakeholders is an essential accelerant especially around the development of an innovation enabling regulatory environment and around the dissemination of sector focused information on uptake benefits, trust and awareness raising.

## 1.7 Key Drivers

The following were considered the key drivers for industrial nations facing demographic change and labour market based limitations on growth, where the adoption of robotics can have a positive effect.

### Economic Drivers

***Labour market drivers:***

In the past robotics has been portrayed as a technology that replaces jobs by providing cost savings. However, labour shortages, labour unavailability and changing work preferences in the population have flipped the motivation for considering robotics. **Robots are now seen as enhancing and enabling the workforce rather than replacing it**.

Mundane, dull and repetitive jobs are hard to recruit to in high value economies and labour shortages are constraining growth in many sectors. Robotics is increasingly seen as the answer.

> *'Manual labour could solve a lot…but it is unaffordable. Only automation can replace the manual labour gap.'*
>
> *'In e-commerce fulfilment performed by third party logistics, customer expectations for next day or same day delivery have changed their business model from "space rental" to "per order fulfilment fee". This means that the more orders they process, the more money they make. These companies are struggling to onboard new customers because they cannot keep up with the orders in an economically viable way without adopting robotic automation.'*
>
> *'Skills shortage (manual labour) is a clear opportunity for service robotics.'*

***Supply chain drivers:***

There are supply chain drivers for greater robotics capability in the manufacturing sector, and in the service sector end users are beginning to recognise that robotics represents an opportunity to raise productivity as well as address the dual impacts of the demographic shift and climate change. They are also aware that robotics can change business models and recognise the need to keep ahead of competitors. This creates pressure on supply chains to deliver and on technology providers and system integrators to deliver defined capability against need. From a supply chain perspective there are also significant scale advantages if cross sector supply chains can be enabled by common standards, development methods and regulatory systems.

> *'The sector is experiencing pressures in supply chains, business model changes, and market failures.'*
>
> *'Standardisation and interoperability are key to supply chain growth.'*
>
> *'Standardisation will expand the market...'*

*'Stronger pipeline of proven developed tech in the UK can "light the way" for future robotic developments.'*

## Functional drivers:

Alongside the economic drivers for robotics there are also a number of related drivers based on the functions that robotics can undertake. These most often relate to tasks that people cannot, should not or will not undertake and to the added benefits that robotics brings to different working environments.

*'There are a lot of "uneconomical" tasks that would help towards net-zero that with the help of automation can be made economically viable. Recycling and precision agriculture are good examples…'*

*'Currently humans are involved in many repetitive and low-skill level tasks, and, in particular with COVID, movement is restricted. Thus, many areas/activities can be left without labour. Also some working areas are not friendly to humans' presence.' All of these can be served (currently partially) by robots.'*

### *Workplace drivers:*

There has been over the last few decades a much increased focus on reducing workplace risk and the development of a culture of safety and the creation of healthy working environments. In addition, it is becoming harder to recruit a workforce prepared to work in challenging environments where the tasks can be characterised as dull, dirty and dangerous. These factors act as drivers for robotics uptake either as tools to increase safety, for example the use of underwater vehicles to inspect deep sea structures such as oil pipelines, or because they provide greater precision, capability or quality in a task.

*'Success has been found in various sectors, e.g. sub-sea, but there is work to be done to persuade firms (a) that robotic systems can produce the desired outcome and (b) they needn't build their own.'*

*'Robotic chemists - routine and repetitive tasks in high-hazard labs; detect and seek out chemicals.'*

*'Novel unmanned / autonomous combat aircraft could potentially outperform conventional manned platforms.'*

### *Information drivers:*

The efficient operation of complex infrastructure such as the transport network, the healthcare system and the energy supply infrastructure increasingly depend on knowledge generated by data capture at source. Robotics can provide a means to capture additional information either as its sole purpose or as a by-product of greater robotics deployment. Organisations managing wide area infrastructure and complex systems, including warehouses and factories see robotics as a means of acquiring better and more accurate asset data that can be used to increase utilisation and efficiency.

*'{robots} Help us make asset management decisions sooner – prevention better than cure etc and are already in demand.'*

*'Turning data into actionable intelligence in real time – avoid information overload.'*

*'Robotics data to feed into Digital Twins to keep updating the model.'*

## 1.8 Key enabling capabilities

The capabilities needed to achieve the long-term goals span technologies, business processes, human capabilities and attitudes, funding, partnerships, policy, standards, and regulation. The following capabilities were highlighted as necessary for growth. In each case the UK has strength in each underlying capability, but these capabilities need to advance within a robotics context to support growth in robotics.

**Digital technology enablers:** notably, the development of digital, AI, and cyber security capability, machine learning (including learning during operations), digital twins, simulation and operation cross-validation. Many applications are enabled by data integration from multiple vendors, for example in connected mobility, requiring global standards and the establishment of trusted, transparent data marketplaces aligned to application development. The UK needs to combine its strengths in these areas and channel them within a robotics context.

*'Data management can be an issue…Vision systems take in a lot of data that you need to be careful storing and using due to personal data (facial recognition).'*

**Systems integration:** in general, system integration is the process of connecting different sub-systems (components) into a single larger system that functions as one. As this term is applicable for all types of systems (hardware, software, physical, etc.) this is applicable also for a cyber-physical system-of-systems such as a robot. In some cases, this integration requires the availability of trusted, public, integrable data sets. The UK robotics sector has key strengths and capabilities in robotics systems integration but needs to extend this to the wider scale integration needed to develop a full cyber-physical capability.

*'Adoption of step-by-step technology evolution rather than going straight to commodity-focused solutions.'*

*'Modular and scalable capabilities enable efficient read-across between use cases and sectors.'*

**Supply chain:** a complete and robust supply chain able to meet the needs of end users. Although some aspects of robotics in a specific sector will require niche design, supply chain growth will provide greater advantage if it is directed across sectors. This relies to some extent on modularity and interconnection between standardised component interfaces. The UK has niche supply chains in the areas that already deploy robotics, greater impact will come from broader cross sector supply chains.

*'Resilience is the key word'.*

*'Needs a UK strategy or it will always follow the market rather than be cohesive.'*

**People and engagement:** skills development, education and training and educating people to use and trust autonomous systems and robots. The UK needs to broaden the base of its robotics skill development and the awareness of how robotic systems impact in specific sectors.

*'Need to educate people about job displacement fears and design suitable systems.'*

**R&D funding, partnering and exploitation, including SME support, for innovation:** Build up and adoption of new technology needs active support for translation and in particular there is a need to ensure that excellent research enhances the UK economy and that SMEs are supported in their journey to deliver value to end users. The UK needs to ensure that innovations reach end users in ways that enhance uptake. Excellent research and innovation needs to be pulled through to market.

*'High priority – needs to include focus on the infrastructure beyond the robot, and training.'*

**Policy, standards, and regulation:** attracting both UK government and international funding together with cross-sector regulation, certification and standards for design, test, and application of robotic solutions in different environments and sectors. The UK needs to create cross sector regulatory norms that enable robotics uptake, for example around the creation of common approaches to the generation of safety cases, or the development of regulatory "sandboxes".

*'Without proper regulation in place, adoption and expansion of use cases are limited.'*

## 1.9 Assessment of UK strengths and weaknesses

### UK Strengths

The UK is seen as having **strengths** in the academic base, including partnering and exploitation for SMEs in sensors, sensing and control systems, condition monitoring, repair and AI. The UK also has strength in its software development ecosystem and in its semi-conductor design industry. Scale up and capability for accelerated technology adoption should, with encouragement, be a practical proposition.

Relative robotics supply chain **strengths** for the UK that also extend to its presence in global markets, were identified in the warehousing, agriculture, medical and nuclear sectors. In addition, deep potential exists in energy, defence (primarily in the UK market), agriculture, aviation, maritime, offshore, and infrastructure sectors. The need to develop a thriving UK ecosystem of start-ups and technology providers was emphasised.

*'Strong domestic capability in developing complex systems (Aero, Defence, Automotive)'*

*'Strong software ecosystem in the UK.'*

*'high quality academic institutions for most of the technologies required.'*

Opportunities for the UK robotics sector exist both for the UK and global markets. The specific UK opportunities that have been identified above, in the form of products, service and solution developments, where considered to be substantial and persistent. The general viewpoint is that UK competitive advantage can be achieved, where there is concerted investment by industry and government.

*'Large organisations should be persuaded to buy-in a service rather than build an internal competitor.'*

*'UK is good for high level of academic engagement. Issue is tailoring academic effort to industry need.'*

*'Important to achieve cross sector engagement.'*

## UK Weaknesses

The participants identified several weaknesses in the UK that are impacting on the ability to take up the opportunities offered by robotics.

***High skills barrier:***

The skills needed for developing and deploying robotics cut across multiple technical domains where the capability in the UK is declining. A renewed focus is needed on training for robotics at all levels of education. In addition, there is a lack of facilities for skills development, education, and training in the combinations needed for effective adoption of robotics.

The skills to deploy robotics, to teach robotics and to operate it are multi-faceted, combining mechanical, electronic, and computational expertise, and there is a lack of suitably qualified and experienced engineers, operators, and more critically of trainers. The UK's poor uptake of automation deeper in the supply chain over several decades has left the UK with a poorer distribution of expertise in automation than some international competitors. This has resulted in difficulties accessing skills development, education, and training.

*'Difficulty of finding skills with the non-standard mix of disciplines involved, due to national barriers to entry, informed customers, lack of Prime System Integrators (both firms and people) and a general shortage of robotics engineers.'*

*'Skills gaps exist in critical areas of robotics, both in quality and quantity.'*

*'Skills gaps exist in research and technician training…'*

*'Robotics is a mixture of a lot of disciplines - which is not a standard educational path.'*

*'Prime System Integrators are lacking in terms of … actual people who understand that role (System engineering).'*

*'Without focusing on training we will not fix the skills gap. This is critical at all levels of education and training from Primary School through Technical qualifications to research level.'*

***Insufficient funding:***

There is a need to establish long term funding mechanisms that avoid the damaging "stop start" funding cycles and the consequential loss of momentum and talent. There is currently a gap between the funding available and what is needed to achieve the desired and necessary progress towards national goals. There are also difficulties around VC level investment in hardware-intensive robotics activities because of the long payback period and higher costs inherent in hardware development when compared to software based investments.

*'…weaknesses will only be amplified if remedial actions are not implemented early enough.'*

> *'Some Government funding for new technologies exists, but needs to be continued and expanded to cover weaknesses.'*

> *'Cross-sector understanding of what robotics can do - i.e. insurance brokers realising they can lower risk by using robotics to monitor assets.'*

### *Poor cross sector regulation and standards:*

While each sector will inevitably have its own specific regulatory requirements and standards there are underpinning methods and processes that can be aligned. To maximise the efficiency of developing and deploying robotics across sectors a degree of regulatory alignment can reduce silos allowing the supply chain to diversify. For example, by developing common, cross sector, approaches to the preparation of safety cases or the validation of hardware. If a component has been validated according to a common validation standard, then it can be used more easily in multiple sectors without having to revalidate it per sector.

Poor cross-sector enabled regulation and standards for design, test, and the application of robotic solutions, especially in environments with diverse regulatory controls, will hold back the development of cross sector supply chains and therefore increase costs and reduce uptake. There is a strong need for cross sector sharing of best practice and the co-development of regulation between the sector based regulatory bodies.

### *Lack of awareness and trust:*

There is often poor awareness of the benefits robotics can offer and a lack of trust in the capability of robotics to deliver real productivity gains. There are also low levels of acceptance of robotics that impact on uptake and acceptability in the workplace driven by the fear that robotics is equated to job loss. The time taken to educate and develop trust has the potential to slow uptake unless these issues are addressed.

> *'Development of autonomous decision making and proof in non critical applications will increase acceptability.'*

> *'Open source tested and certified framework can accelerate and enhance technology adoption through trust.'*

### *Business model disruption*

The potential impact of robotics on business models can be seen as disruptive rather than an opportunity. This can develop pressures in the supply chain and lead to market failures when adoption is stalled because of reluctance to make business model changes needed to fully exploit the benefits of robotics.

> *'Changing the business model allows the methodology to be changed, supporting service robots carrying out tasks lower on the value chain even within the profession of skilled humans, i.e., Chemists aren't hired to pipette and weigh, but to plan experiments and analyse results…'*

### *Fragmented supply chain:*

While the supply chain for industrial robotics is global and well established the supply chain for service robotics is fragmented and incomplete. While to some extent this is true globally there are strong supply chains for drones, under water inspection systems and other specific areas of service robotics. The robotics sector in the UK and globally is still small and nascent and stimulation of a complete supply chain is needed.

> *'Activity required to bridge the gap between robotics providers, end-effector development organisations, system integrators, and end users.'*

### *Accessibility of test and validation facilities*

There is insufficient accessibility to test and validation facilities for SMEs. SMEs in particular need to be able to prove their technology can deliver value to an end user without risking IP leakage. This may require access over an extended development time to specialised testing facilities. For example, a private road network, sewer pipes or rail network infrastructure. Innovation uptake can be accelerated by developing access mechanisms to facilities that already exist, or by creating facilities, either in or between sectors, that are managed to provide access to SMEs or higher TRL research projects. This lack of access also extends to the capabilities needed to utilise digital twins and simulation to provide validation, these processes often involve access to considerable amounts of specialised data and digital models and to computation capacity sufficient to provide high quality simulation environments.

> *'No facilities and test centres allow SMEs to rent time on precise testing equipment.'*

## Key enabling actions

Based on the above analysis of UK strengths and weaknesses the participants identified the following enabling actions as a priority:

*Enhance uptake:*

- Improve the UK skill base and develop higher levels of sector awareness around robotics capability.
- Improve cross sector regulation and standards for design, test and validation to enable greater uptake of robotics.
- Building scale up and adoption capability across multiple sectors.
- Raise levels of trust in robotics and its deployment.

*Enable supply chains:*

- Strengthen supply chains to ensure full capability exists to meet national need.
- Attract international funding and increase UK funding for robotics across the range of sectors and technologies.
- Stimulate collaboration between robotic development organisations and those creating and proving systems supported by funding agencies and knowledge transfer organisations.

*Ensure pull through:*

- Strengthen the underpinning technical base covering critical robotics technologies and application oriented technologies.
- Create funding to drive R&D and uptake, partnering and exploitation including SME support.

- Develop mechanisms to accelerate technology adoption from academia to industry.
- Actively connect the thriving UK ecosystem of start-ups and technology providers.

## 1.10 Forecasting the evolution of service robotics to 2032 and beyond

The following summary integrates outputs from the various focus areas and presents a combined high level view of the trajectory of service robotics from a global perspective. If the UK coordinates its support for robotics in the public and private sectors then it can expect to see similar developments at national scale. Failure to keep pace will cut the UK off from the advantages that robotics will bring making it a technologically dependent state rather than a "science driven superpower".

### ***Current state***

*Systems and use cases:*

Some market/application-specific robotic systems with different degrees of automation have come to market across a range of niche application areas including subsea, nuclear, healthcare, agriculture and transport. These retain 'human in the loop' for reliability, regulatory and business case reasons, particularly for high-value/high-hazard operations.

*Technologies and functional capability:*

Current technology enables certain simple tasks to be executed in well defined and stable environments, mostly through robot co-existence. Currently deployed systems have limited collaboration and are characterised by limited situational awareness, basic collision avoidance, and low levels of manipulation dexterity and low levels of autonomy. Systems are developed in niches where capabilities can be tailored to operating conditions.

*Markets and supply chains:*

Some design services exist within specific sectors, but off-the-shelf tools and systems need customisation for use in specific domains. Supply chains are fragmented, with end users lacking understanding, and with the knowledge gap creating conservative and risk averse approaches. There is a lack of trusted exemplars; however, many use cases are being explored. There are significant issues in recruiting developers with robotics knowledge.

### ***Short term 2023–2026***

The evolution in the short term relates to the development of confidence in robotics, improved understanding of capability, end user skills and the improvement of core technologies aligned with key aspects of national and industrial need.

*Systems and use cases:*

- Semi-remote, off-the-shelf solutions perform individual and well-defined tasks in service and industrial applications – for example the use of drones.
- Collaborative and shared workspace applications increasingly used in industry.
- Extended use of teleoperated systems in the energy sector and some highly specific healthcare procedures.
- Increasing numbers of inspection tasks carried out using remotely piloted aircraft and specialised underwater vehicles.

*Technologies and functional capability:*

- Deployable incremental improvements made to technical capabilities in dexterity, navigation, mapping and task and mission planning and control.
- Teleoperation employing advanced/enhanced features/capabilities, such as augmented reality and 3D visualisation, in conjunction with limited built-in autonomous functions becomes "business as usual" in some high-value/high-hazard operations.

*Markets and supply chains:*

- New business models, for example for solution performance and risk-share investment and delivery have emerged, which support the exploitation of service robotics technology.
- End users are becoming more aware and start to see the potential of robotics uptake.
- There is wider investigation of the adoption of robotics across different application sectors and a growing understanding that robotics could solve specific problems.
- There is ongoing review and adjustment being made to regulatory environments in order to enable robotics to operate more widely and in public environments under controlled conditions.
- The development of advanced regulatory "sandboxes" is progressing on a sector by sector basis and this is informing a strategic approach to regulatory reform.
- Supply chains are starting to mature around sectors and there is growth in the service delivery side of robotics.
- Training programmes covering robotics skill development are beginning to emerge.

*The following projections are based on an optimal trajectory of 'best in class' usage.*

### *Medium term (2027–2032)*

*Systems and use cases:*

- Some sectors who were early adopters are starting to transition to early majority use.
- Supply chains for robotics in sectors other than manufacturing are becoming well established.
- Robotics is seeing strong double digit growth globally.

- Complex infrastructure in transport and the utilities are increasingly using robotics based systems both for mobility, asset management and installation.

*Technologies and functional capability:*

- Dedicated silicon for robotics applications is being produced, primarily in sensing, actuation and energy management. There are strong links to component supply chains in the automotive sector.
- Increasingly novel form factors are being used in applications with the first examples of soft robotics being commercialised.
- Strong standards are emerging around interoperability and modularity, these are becoming embedded in supply chains and component design.
- There is a significant increase in sector based design and configuration tooling that uses AI to assist in the assembly and configuration of robotics systems and their integration into existing systems.
- Increasing use of synthetic environments and digital twins are impacting on the use of robotics in complex operating environments such as transport, healthcare, logistics and cities.
- Sensor form factors are becoming smaller and cheaper enabling greater levels of data capture and improved interpretation of the operating environment.

*Markets and supply chains:*

*End user pull:*

- End users have become experienced and educated buyers and collaborators. and are aware of the availability of businesses that can deliver solutions tailored to their needs.
- Establishment of cross sector supply chains through increased modularity are enabling supply chains to emerging capable of serving diverse market segments.
- A stronger skill base evolves, including different areas of industry developing multiple levels of skills to enable operational and strategic decision making.
- As incentives for adoption by industry and public awareness of the level of capabilities are raised, key components and regulation improve.
- Robotic systems are increasingly used to support remote operations for the maintenance and repair of complex assets.

*Technical advance:*

- Technical improvements continuously reduce the need for human intervention in hazardous environments.
- Safety and cybersecurity are increasingly “built in” to hardware and safety in unrestricted environments is becoming certifiable.
- Systems are able to interpret and react to a wide variety of failure modes and reliability issues, including human error.
- Sensing (sub-)systems include sensors/sensor suites integrated with computing, which builds additional capabilities supporting data fusion.
- Advances in AI have significantly impacted on the ability of robotics to interpret complex human environments enabling multiple new use cases and extending the capability of interaction with humans.

*Regulation:*

- A refined and more structured regulatory framework is in place. A UK robotics end-to-end ecosystem is established, which helps the robotics industry deliver the needs of a variety of end users through funding and testing facilities[24].
- Regulation is starting to drive technology uptake.
- As regulation and understanding of industry capabilities develop, more test facilities for end-to-end testing and validation including niche trials are provided.
- Legislation and regulation “catch up” is accelerating – new regulatory frameworks are developed and old frameworks modified, supporting niche and needs-based adoption (driven by competition and market forces in different manners in different sectors).

### *Long term (2032+)*

*Systems and use cases:*

- There is a high level of collaboration between human–robot and robot–robot multi agent systems carrying out and optimising complex tasks, operating increasingly autonomously in unknown environments.
- Systems have high situational awareness, including of humans and other autonomous agents.
- Many robotics systems are fully integrated with digital twins, and decision making, task and mission control is fully distributed and autonomous.
- The fusion of data is not restricted to the system itself but takes place across multiple systems including remote (e.g. satellite) and embedded data sources.
- Maintenance systems are mostly autonomous.

*Technologies and functional capability:*

- Innovation is focused on improved cost effectiveness at scale and higher levels of performance and reliability.
- Some general purpose systems are being produced able to carry out multiple tasks across different service sectors.
- Dexterity is exceeding human capability in unstructured tasks both in terms of accuracy and speed.
- Certifiable guaranteed collision avoidance is possible in many areas of operation including air and road transport.

*Markets and supply chains:*

- Convergence of different hybrid business models offers complete permanent automation (‘robot in a box’, long-range explorations), on-demand mobile services, strategic control by human operators and coordinated resilient multi-robot autonomy.

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[24] For instance, living labs and government provided test infrastructure for companies operating at low Technology Readiness Levels. An example is the Cyber-SHIP lab at the University of Plymouth, UK (https://www.plymouth.ac.uk/research/cyber-ship-lab) that operates as a cyber security testing facility for the offshore wind sector.

- Using robotics to solve a problem is just as accepted and widely adopted and understood as a human-based solution.
- There is systemic adoption, with only traditional sectors that rely on artisanal methods not adopting robotics approaches.
- There is a fully integrated, well-established supply chain, streamlined to end user requirements.

## 1.11 Value Creation

In the context of products services or system developments emerging from the consultation process the following areas of value creation opportunity for the UK were identified:

- Surveying, inspecting, and mapping robots.
- AI and robotic system design, build and operation.
- Mobile robots.
- Robots with manipulators/end-effectors to perform various tasks.
- Human, robot, and intelligent systems collaboration/co-working.
- Sensors and sensing systems design, build and operation; awareness/perception/navigation and SLAM.

**In each of these areas there was consensus within the participants that the realisation of these opportunities for the UK was feasible, that the capability to achieve them was available and that adoption could be achieved with concerted investment by government and industry.**

The following sections detail each of these areas and provide some insight into the sectors where each area can have impact, the key enablers for value generation, from an end user perspective, and of the benefits that can be derived from uptake. These sections also detail the expected long term development of each area. In each section the perspective taken is from the supply chain looking towards market generation with end users and the impact on application use cases.

### Surveying, inspecting and mapping robots

Surveying, inspecting and mapping robots are the current core applications in the professional service sector where robotics is already proven to effectively automate and augment manual approaches. These range from gathering and assessing information about assets, infrastructure, plant, etc., to overseeing their operation. Robotics provides the opportunity to carry out tasks in inspection and remote maintenance, providing greater levels of safely at lower cost, especially in operating environments that are hazardous, inaccessible or are spread over a wide area such as transport networks, energy or water supply infrastructure or large scale industrial plant, amongst others.

There is a recognition that robotics will transform and disrupt business models in some sectors but in return it will reduce the need for humans to carry out high risk or dull and repetitive tasks. Robotics carries the potential to improve the utilisation of assets and extend their lifetime and performance.

*Key enablers:*

- Wide spread end user awareness of market opportunities.
- Proof of robotics capability from a reliability and regulatory perspective.
- Active adoption by end users pivoted on awareness of sector benefits.
- Development of cross sector regulation standards and shared knowledge.

*Key benefits*

- Increased asset data quality, increased capture frequency and higher levels of data registration between capture cycles enabling more in depth analysis over time.
- Greater ability to correlate faults across similar assets.
- Greater consistency of repairs and maintenance actions across assets.
- Reduction in asset failure risk and consequent liability created by increased validity of asset knowledge.
- Reduced maintenance down time, and reduced risk of unplanned maintenance.
- Increased levels of safety for workers and improved working conditions.

*Key sectors:*

- Transport infrastructure: inspection, maintenance and operation of rail, road, air and sea assets.
- Food production: Land and herd management, factory farms, harvesting, processing and distribution.
- Energy and water Infrastructure: Distribution systems, installation and decommissioning, fault detection and repair.

Other application areas include, emergency services, healthcare, construction, large industrial plant and logistics all of which can potentially benefit from robotics deployment. Even the insurance sector may benefit from improved inspection of plant and the consequent improvement in risk assessment.

*Vision over time:*

- Improvement of inspection quality with robotics enabling capture of a wider range of data coupled to denser inspection regimes at lower cost where the deployment of robots is cost effective against savings in lifecycle costs.
- Increasingly automated remote maintenance, particularly in hazardous and unsafe environments; for example in transport, nuclear, offshore and energy infrastructure.
- Progressively transformed business models adapted to extract greater value from a robotics focused or robotics augmented operational methods.
- Improved human oversight of highly complex operations improving efficiency and utilisation of assets and the oversight of large scale projects.

## AI and robotic systems design, build and operation

Value creation opportunities exist in developing value around the existing system design, build and operation capability in the UK. In this area there are three primary opportunities for value creation. **The first** opportunity is driven by the market need to create underlying components and sub-systems that can be used in common across sectors to build robots. **The second** opportunity arises from the need to assemble these components into systems that match the specific demands of end user applications. To date service based robotics typically requires bespoke configurations for each application in each sector. Value is created from the development of system integration skills for a specific sector that require the combination of robotics knowledge with sector application knowledge about processes, regulation and practice. **The final** area of opportunity is in the management and operation of robotics on site. This ranges from direct teleoperation, for example drone operators that must be qualified to fly or surgeons practiced in robotic laparoscopy, to the remote and onsite management of multiple interacting robotic systems on a construction site or farm.

Cost effective design build and operate processes are essential for wider sector uptake. The highly bespoke nature of robotic installation currently holds back many areas of potential application because of the high cost of design and build.

*Key enablers:*

- Cost, labour and sustainability drivers in end user sectors creating the need to deploy new methods.
- The need for end users to extend plant lifetime, reduce maintenance costs and increase worker safety.
- Ability to accelerate component based system integration rather than engage in full scale bespoke design and build.
- End user demand for higher levels of robot system functional reliability, lower costs and faster means of adaption to new requirements.
- Reduction of operator training and specialisation needed to operate and maintain robotic systems.

*Key benefits*

- Ability to deliver incremental functions and performance improvements within the same "system envelope" thereby delivering a more flexible and adaptable system.
- Development of UK sovereign capability in critical areas of national importance from defence to infrastructure.
- Delivery of increased investment confidence for end users and clarity on their return on investment.
- Lower costs bought about by cross sector supply chains.

*Key sectors:*

- Sectors where periodic inspection and maintenance are a regulatory requirement or where it ensures improved asset utilisation or extended life; for example bridge inspection across the transport infrastructure.
- Sectors where labour availability is a limit on productivity.
- Sectors where multiple complex factors need to be optimised to maximise efficiency such as in logistics, wide area transport, healthcare provision and construction.

- Where sharing of modules or components cross sector can accelerate uptake and reduce costs.

*Vision over time:*

- Regulation and certification have caught up with technical capability to allow the operation of remotely monitored robotics systems in public spaces.
- There is timely alignment between the progression of technical capability and the exploitation of that capability within sectors.
- The use of robotics in the service sector has become the norm.

## Mobile robots

Mobile robots present an extensive range of value creation opportunities. They have the potential to be used in all sectors and in all operating environments. They are characterised by being able to autonomously navigate through an environment and reach a given destination or goal, they can follow a specific path or create a pattern of movement, for example to fully cover an area, within that environment. They fulfil a wide range of different use cases and can be used in teams or swarms. Some examples are:

- The transportation of people or goods between destinations. For example, in a factory or warehouse.
- The surveying of an environment capturing specific data about the environment potentially using multiple types of sensing. For example, in the surveying of crops with an infra-red camera or making a radiological survey of a contaminated site.
- The application of systematic processing over a defined working environment. For example, spraying or cleaning an area or harvesting a crop.
- Carrying out a specialised task at a specific location for example drilling for and collecting planetary rock samples, or the repair of potholes.

Mobile robots will become ubiquitous and developing core capability in the UK to design, create and deploy mobile robots is a key part of the deployment of robotics overall.

*Key enablers:*

- End user awareness of the potential for application and the benefits of deploying mobile robotics.
- Demonstrable efficiency and cost savings when deployed in end user application environments.
- Increasing use in the supply chains of closely related sectors stimulating knowledge and method exchange.

*Key benefits*

- Ability to deliver tools and functions to remote, hazardous or inaccessible working environments.
- Improved performance levels driven by increased positional accuracy, localisation and coverage.

- Improved data collection capability in terms of data accuracy and repeatability as well as frequency and modality of collection.
- Mobile robots coupled to robot arms and end effectors allows processing to be taken to where it is needed. For example, airport runway repairs.

*Key sectors:*

- Applicable in all sectors that require areas or volumes of an environment to be "processed" in some way.
- Applicable in all sectors that involve short or long distance transportation.
- Applicable in sectors where there are complex or hazardous environments where humans should not, cannot or will not go.

*Vision over time:*

- Increase in the level of environmental complexity that can be successfully navigated autonomously.
- The level of trustworthiness in completing tasks has reached a point where trust has become implicit.
- The ability to handle unexpected complex events impacting on the environment has reached a point where robots can be deployed successfully in dynamic environments. For example, in care homes.
- The ability to autonomously carry out increasingly complex tasks at remote or hazardous sites with guaranteed levels of performance has increased to the point where robots are enabling new markets.

## Robots with manipulators/end-effectors to perform various tasks

This area of value creation is seen as the heart of many different use cases across multiple sectors. Robots having multi-jointed arms with end-effectors that are able to sense, pick, carry, assemble, disassemble, orient and sort objects have application across all sectors. They are traditionally found as fixed installations in manufacturing and are a familiar sight in car and electronics mass production factories but can also be found in agri-food, healthcare and logistics. More recently arms and end-effectors can be found coupled to mobile robots of all kinds from land to air and space to underwater. Arm and end effector combinations may be found singularly or in pairs mimicking the placement of human limbs. End effectors may be general purpose or highly task specific and may also be interchangeable. End effectors may also be dedicated to sensing modalities that require close proximity or contact with the sensed object or surface, such as X-Ray or Ultrasonic sensing.

While there are use cases where such systems can be operated autonomously these are limited to highly constrained environments, such as welding car body parts. To date deployed systems are typically unable to handle high levels of environment and part complexity and in many cases use human teleoperation augmented by limited autonomy, for example to constrain motion or ensure the end effector is kept within a well defined operating space.

These systems are the "bread and butter" of robotics and underpin multiple critical use cases. Having the capability to address key end user needs, and support deployment of robotics in key sectors for example in medical, nuclear or underwater, is an important area of value creation for the UK.

*Key enablers:*

- Ease of programming and learning of new tasks ideally with a “zero code” approach.
- Faster redeployment to new tasks enables greater use in lower lot size production.
- Greater awareness of how to integrate arms into more specialised production environments in midsized and small manufacturing operations.
- Greater range of part handling with fewer end effector changes.
- Greater standardisation of hardware and interfaces enabling wider supply chain choice and better utilisation of devices.
- Clear guidance and understanding of equipment choices when carrying out system integration.

*Key benefits:*

- Improved productivity through higher levels of automation in handling and assembly tasks.
- Removal of the need to off-shore production in low wage economies.
- Improved working conditions through automation of repetitive dull tasks.
- Extension of mobile robotics applications with local manipulation, assembly and processing capability.

*Key sectors:*

Robot arms with end effectors are already deployed in mass manufacturing and elsewhere in the manufacturing sector. The opportunity to develop new market value depends on the extension of technical capabilities- increased payload, increased dexterity, increased accuracy and increased compliance for direct interaction with human operators. New sectors will emerge with increased technical capability and ease of reconfiguration.

- Highly specialised arms and end effectors for novel environments; for example, ultra light-weight arms for use on drones; radiation hardened arms for use in nuclear and space, waterproof pressure tolerant arms for use undersea.
- Sectors where mobility coupled to arms and end effectors adds value; for example in agriculture, logistics, healthcare and inspection and maintenance.
- Sectors with highly repetitive assembly or maintenance tasks, or where remote maintenance can improve or sustain asset availability.

*Vision over time:*

- End effectors become increasingly able to handle more complex objects autonomously or carry out a wider range of tasks without tool change.
- Arms are able to safely apply force to work pieces in close human proximity.
- The configuration and adaptation of arms and end effectors to new tasks no longer requires specialised robotics knowledge and can be carried out in the work place.

- The supply chain for components has reached a point where interoperability between components from different suppliers is not only expected but automatic, just as it is with IT based architectures such as Wi-Fi and USB.
- The availability of mobility plus dexterity has become a common tool in multiple sectors from energy supply to agri-food.

## Human, robot, and intelligent systems collaboration/co-working

A primary trend in robotics is towards collaborative robotics; not replacing people with robots but augmenting human tasks by providing the capability to carry out tasks more safely, with less waste and with greater efficiency, accuracy and repeatability. This is driven by two factors:

- Firstly, the technology to provide robots with fully autonomy in any task does not yet exist and is not expected to exist for some time and so human involvement "in the loop" is needed to provide high level planning and guidance.
- Secondly our societal acceptance of poor working conditions, of unsafe practice, and of workplace risk has reduced significantly over the last few decades. There are now numerous areas of work where it has become almost impossible to recruit workers even in tasks that require high levels of skill, for example in welding. Robotics is both a means to make these tasks safer and therefore more acceptable.

Collaborative robotics involves close interaction either through collaboration in a shared workspace or through direct human control such as in the use of exo-skeletons or teleoperated systems, such as surgical robotics. In such cases the robot is usually providing valuable assistance to maintain safety or increase performance levels or provide accessibility or dexterity, for example hand tremor removal in assisted surgery.

*Key enablers:*

- Improved understanding of the barriers to collaborative working.
- Standardised training for workers to upskill to robotics based working.
- Improved availability of evidence based assessments of the value add of robotics on a sector by sector basis.
- Clear processes for assessing the safety case and the economic return on investment.
- Improved understanding about the appropriate handover of control between robot and human during task execution, including social norms and for example non-verbal cue interpretation, social context etc.

*Key benefits:*

- Reduction in worker injuries due to physical stress for example when lifting or when repetitively carrying out assembly tasks.
- An improved and more acceptable working environment.
- Improved performance outcomes in tasks.

*Key application areas:*

- Tasks where job quality can be enhanced through augmentation.

- Sectors where dull and dangerous jobs can be made more acceptable and rewarding.
- Use cases where human augmentation raises performance levels and increases the likelihood of a successful outcome.

*Vision over time:*

- Increasing improvements to working conditions through the adoption of collaborative robotics working.
- Increasing ability to work collaboratively over longer periods of time, increasing levels of synergy between human and robot.
- Robotics augmentation contributing to higher levels of performance in increasingly complex and more dynamic tasks driving up competitiveness.
- Increasing levels of augmentation and collaboration being more widely adopted as technical capability increases.
- Larger numbers of collaborative tasks being undertaken in a wider range of sectors.
- Trend towards multiple people and robots collaborating as a group to achieve a task with greater safety and productivity.

## Sensors and sensing systems design, build and operation; awareness/perception/navigation and SLAM

While current robotics technology is capable of delivering functional systems to end users there are key areas of technical development that are needed to create greater functional capability, that will in turn open new areas of application.

There are significant value creation opportunities in the development of sensors and sensing systems and in the delivery of system components able to interpret, map and analyse the data delivered by those systems. These range from visual interpretation of scenes to the interpretation of data from a wide range of different sensor modalities; acoustic, chemical, radiological and tactile for example. In particular opportunities exist in the interpretation and analysis of correlations between sensor modalities, such as acoustic to visual.

Value creation exists in the provision of components that embody and integrate sensing and interpretation skills that can be used “on-device”, to the provision of services external to the robot as well as for processing and integrating robot derived data with data from fixed assets. For example, transport network crowd flow monitoring from train based data (e.g. assessment of who or how many will exit at the next station) and fixed cameras on platforms and concourses looking at platform occupancy and trends. Sensing systems will contribute to local decision making as well as high level management and control systems.

*Key enablers:*

- Improved sensor technologies coming from fundamental research, e.g. quantum sensing, novel materials etc.
- Improved methods for sensor information processing including multi-modal integration.

- Standardised sensing packages, hardware and software, and sensor data with knowledge sharing protocols.

*Key benefits:*

- Allows decision making, both local and system level, to be based on a wider range of knowledge derived from sensing.
- Improved levels of functionality including dexterity, planning, autonomous decision making, and context awareness based on improved data capture and interpretation.
- Performance improvements based on increased access to knowledge about the working environment derived from real time data.
- Improved data interpretation driving digital twins and long term data interpretation over extended time scales.

*Key developments:*

- Robotics dedicated sensor integration and processing on device to reduce cost, sensor size and power consumption.
- Improved core sensing technologies; including improved miniaturisation, integration and on-device calibration.
- Novel innovations particularly in;
    - force sensing and control,
    - miniaturised and modularised biological and chemical sensors,
    - improved information and cognitive sharing between robots,
    - methods for coordinating robots to collaborate in mapping and data collection tasks.
- Industry specific sensing technologies refactored for robotics use, for example, miniaturised mass spectrometry at an end effector.
- Integrated data handling, both onboard and offboard, enabling deeper data interpretation driving decision making and digital twin collaboration.

*Vision over time:*

- Increased ability to easily create novel form factors that fit a wider variety of tasks: for example, working inside pipes, or through restricted portals.
- Higher levels of reliability and trustworthiness for sensor packages and full mapping of capability fit to application need at data and decision levels.
- Increased ability to move from simulation to the real (physical) world via high accuracy/fidelity testing/simulation.
- Improved ability to validate and certify components and sub-systems at greater levels of complexity of task and environment.

# Recommendations

## 1.12 Key messages

In response to the objectives set out for the project, participants emphasised the importance of articulating a vision, encouraging a mindset change towards the wider use of robots, enabling innovation, and coordinated collaboration. In the UK particularly, strengthening the supply chain and improving connectivity between UK research and industry must be prioritised.

## 1.13 Recommendations

Participant recommendations focused on practical action:

- Establish/enable necessary institutional mechanisms and processes to address the actions identified by this consultation process and develop associated remits to ensure that identified UK capability gaps and barriers are addressed.
- Identified actions include the following:
  - Institutionalise cross-sector learnings through networking and coordination.
  - Build scale up and adoption capability (including R&D funding, partnering and exploitation including SME support).
  - Create infrastructure(s) enabling sharing of data or training outcomes among different ML or AI robotic (sub-)systems.
  - Fill the gaps in the incomplete value chain (priority sectors and capabilities identified).
  - Develop regulations to enhance innovation in the field, particularly regarding application of emerging technologies.
  - Develop programmes for education, training and skills development.
  - Establish links to appropriate finance and provide independent expertise to support scale up and deployment.
  - Improved and more comprehensive coordination/sharing of various activities including marketing and components/sub-systems/systems assessment (including co-simulation infrastructure).
  - Fund/support for international presence.
  - Fund/support focused robotics and AI research and innovation activities including industrialisation[25].
- Collaboratively develop a cohesive UK approach to integrate with other, related programmes and build a UK 'robotics cluster' to:
  - Share knowledge and experience.

[25] Industrialisation corresponds to pre-commercial activities, taking a proof-of-concept prototype to a system robust, effective and open enough to be used for extensive testing and verification/validation in realistic or operational environments.

- Demonstrate the value of robotics by identifying growth areas to build demand and output.
- Develop skills and training requirements.

# Appendix 1: Definitions

**ROBOT**: We consider that a robot comprises a system of interconnected, computational, cognitive, and physical tools, or 'machines'[26] able to appropriately perceive its environment(s) and control its actions, performing useful tasks for humans in the real world, and that they can be remotely controlled, automated and smart or autonomous.

Various other classifications of robots/robotic systems also exist, such as, manipulation, mobile and data acquisition and control.

In this report, a robot or robotic system is seen as a system-of-systems (SoS) created by heterogeneous collections of physical and information resources joined together by intricate physical or logical connections and interactions. As the term implies, an SoS consists of components that are themselves systems**.**

**SERVICE ROBOT or robotics**: Refer to section 2.1 Robot categories & applications

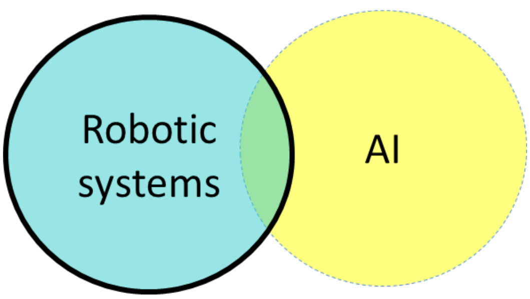
**INDUSTRIAL ROBOT or robotics** (as per ISO 8373:2021)
Is an automatically controlled, reprogrammable multipurpose manipulator programmable in three or more axes, which can be either fixed in place or fixed to a mobile platform for use in automation applications in an industrial environment
The industrial robot includes:

- the manipulator, including robot actuators controlled by the robot controller.
- the robot controller.
- the means by which to teach and/or program the robot, including any communications interface (hardware and software).

Note that in the engineering literature service robots are usually described as the technological evolution of industrial robots, mainly because the environment of operation or application area is considered to be technically more complex.

**AUTONOMY:** According to ISO 8373 robots require 'a degree of autonomy', which is the 'ability to perform intended tasks based on current state and sensing, without human intervention' [27]. For service robots this ranges from partial autonomy – including human robot interaction – to full autonomy – without active human robot intervention. Service robots are categorised according to personal or professional use. They have many forms and structures as well as application areas.

**ARTIFICIAL INTELLIGENCE**: There are many different definitions of artificial intelligence (AI), but we consider AI to be the merging of science, engineering, and technology with the objective of making a computing system, or machine, to demonstrate human-like behaviour in many broad and varying contexts.




[26] Robots can thus be classified as a subset of cyber-physical systems (CPS).
[27] Note that many different definitions exist for autonomy.

For the purposes of this report, AI is considered only to the extent that is being employed with/within physical machine(s) to create robotic system(s); usually, but not only, towards achieving 'a degree of autonomy'. As shown in the diagram, only the blue area is addressed.

## Related programmes

As indicated in section **Error! Reference source not found.**, participants identified as a current barrier the lack of connections between initiatives related to service robotics across a range of sectors. Sharing knowledge and experience from UK programmes could become a potent enabler. Relevant programmes identified by participants are shown in Table 1.

**Table 1: Initiatives mapping**

| Categories | Programmes/Agencies[28] | Region/ Area |
|---|---|---|
| **Bodies/ Organisations** | York Trusted Assurance for Autonomy (Academic) | UK |
| | DASA, Regional Defence & Security Clusters (RDSC) | UK |
| | Dstl | UK |
| | CPI | UK |
| | Net Zero Technology Centre | UK |
| | UKSA Robotics Programmes/Satellite Applications Catapult. | UK |
| | euRobotics | EU |
| | RACE UK atomic energy | UK |
| | Sprint Robotics | Worldwide |
| | UK RAS | UK |
| | Robotics Growth Partnership | UK |
| | International Federation of Robotics | Worldwide |
| **Initiatives/ Activities**<br><br>**(Existing/ongoing as of May 2022, unless otherwise stated)** | Potential Digital Twin infrastructure (DTI) - National digital Twin - The RGP initiative. (Future initiative) | UK |
| | CyberASAP (Cyber security initiative) | UK |
| | ISCF – RfaSW, Longops (Nuclear) – Completed | UK |
| | Von Braun Space Hotel (2025) - Planned | USA |
| | IUK Robotics Hubs, NCNR, ORCA, RAIN (finishing soon), FAIR Space Hub. - Completed. | UK |
| | IUK National Robotics Proving Grounds – Future initiative | UK |
| | The Farming Innovation Programme – DEFRA | UK |
| | IUK Future Flight Innovation programme | UK |
| | IUK Small Business Research Initiative | UK |
| | Robotics for a safer world challenge – (e.g. Astroscale) | UK |
| | Drone – Pathfinder | UK |
| | Future Capability Group – Project Theseus | UK |
| | EPSRC – Trusted Autonomous Systems Network/Programme | UK |
| | BEIS – Enabling a national Cyber-Physical Infrastructure to catalyse innovation – Future initiative | UK |
| | Eurostars / Eureka / Horizon 2022 | EU |
| | Robotics systems of systems (CORTEX) | UK |
| **Test facilities** | The 5G Test bed accelerator – Cambridge Wireless/Huawei | UK |
| | Plymouth Smart Sound | UK |
| | RAICo | UK |
| | MTC | UK |
| | DARE Centre | UK |

[28] Text in the column contains hyperlinks which are all accessible as of 30 May 2022

| | | |
|---|---|---|
| | Satellite Applications Catapult | UK |
| | Battlelab | UK |
| **Trade Associations** | Energy Industry Council | UK |
| | Automate UK | UK |
| | Manufacturing Technologies Association | UK |
| | | |

# Appendix 2: Process

## Background and scope

The framework for this work considers the 'value chain/constellation' view of the service robotics shown in Figure 1.

Furthermore, the perspective taken is from the UK's 'upstream' value chain looking towards both the UK's and rest-of-the-world end users/beneficiaries, as shown in Figure 2 in the yellow highlighted area.

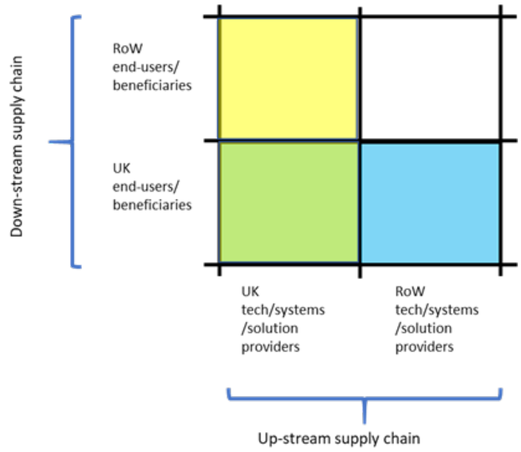



**Figure 2: Supply chain mapping**

This is different from the approach taken in the BEIS Research Paper 'Robotics and autonomous systems: the economic impact across UK sectors', in which the view taken is the UK's end users/beneficiaries (the blue highlighted area in the diagram). Thus, the two reports should be seen as complementary to each other, addressing different aspects of the UK service robotics landscape.

The work was designed to provide a broad landscape view of the service robotics sector, to develop a vision for a stronger UK sector, to identify strategic capabilities essential for its achievement, and to identify (within broad timescales) the R&D&I pathways required.

The scope of the roadmapping exercise was envisaged as the entire value chain of service robots, comprising RTOs; RAI technology and sub-system suppliers; RAI system integrators; RAI service providers; RAI and other end users; standards defining organisations; regulatory bodies; industrial environment; manufacturing; and electricity, gas, steam, and air conditioning supply. The roadmap would have a ten-year perspective (2022–2032).

IfM Engage was tasked with extracting market and business drivers from industrial sectors across manufacturing and beyond. The latter included: agriculture, forestry, and fishing; mining and quarrying; water supply – sewerage, waste management and remediation activities; construction; generation aspects of electricity, gas, and steam; repair of motor vehicles and motorcycles.

The work was driven mostly by 'market pull', and the technological innovations that have been identified are such that they can anticipate future application areas/market segments; it was not driven by 'technology push', or what can be done with the existing stock of technologies. The work builds a vision of where the industry wishes to go and what technologies or interventions are needed to get there. The roadmap thus should help companies or organisations identify, select, and develop the right technologies or business models needed to create the right products and services for future markets. The scope of work did not intend to identify or prioritise the main application areas/market segments for the adoption of robotics in the UK; simply some of them were identified as good candidates for 'market pull' during the road-mapping process.

## Overview

This project used a roadmapping approach developed at the IfM, University of Cambridge. The work began with desk research of previous studies and reports. Notably, the 'value chain/constellation' view of the service robotics value chain was adopted to inform the roadmap taxonomies (**Error! Reference source not found.**).

Delegates from a range of companies, research institutions and government agencies then took part across five 2.5-hour virtual workshops to develop and assess the service robotics landscape. (Participant organisations are listed in appendix 2.) Desk work was used to create a straw man 'landscape' for the evolution of the UK and global service robotics industry, which was issued to participants for their review and further comment in advance of the workshops.

Key outputs from these workshops were seven 'value creation' roadmaps, each focused on a group of products, services and solutions identified as substantial and persistent opportunities by the delegates during the landscape assessment.

Desk work by the IfM Engage team then used the individual workshop outputs, supplemented by insights from the desk research, to create i) an integrated road map, ii) a draft vision for the roadmap and iii) an analysis of global strengths, weaknesses, opportunities, and threats (SWOT).

Finally, participants in three further 2.5-hour virtual workshops were tasked with reviewing and refining the outputs and assessing UK-specific aspects, identifying linkages to other programmes, and developing key messages for stakeholder audiences.

## Approach to creating the integrated roadmap

In the IfM roadmapping model, initial landscaping work identifies and links trends and drivers and capabilities to generate proposals for prioritised products, services, and solutions. These prioritised topics are developed in syndicate groups as roadmaps, which are subsequently reviewed and integrated into a single roadmap. From the integrated roadmap a high-level vision is developed.

### *Desk study*

Innovate UK supplied the model of the service robotics value chain (**Error! Reference source not found.**) which was adopted to inform the roadmap taxonomies. Desk work began with the investigation of previous studies and reports. This work created a significant input to the roadmapping activity which followed and allowed the development of an effective taxonomy. It is the subject of a separate report.

### *Straw man landscape*

The learning from the desk research was then used to create the first element of roadmapping: a straw man 'landscape' for evolution of the UK and global service robotics industry. This straw man landscape was issued to participants for their further comment in advance of the workshops.

### *Landscape layers*

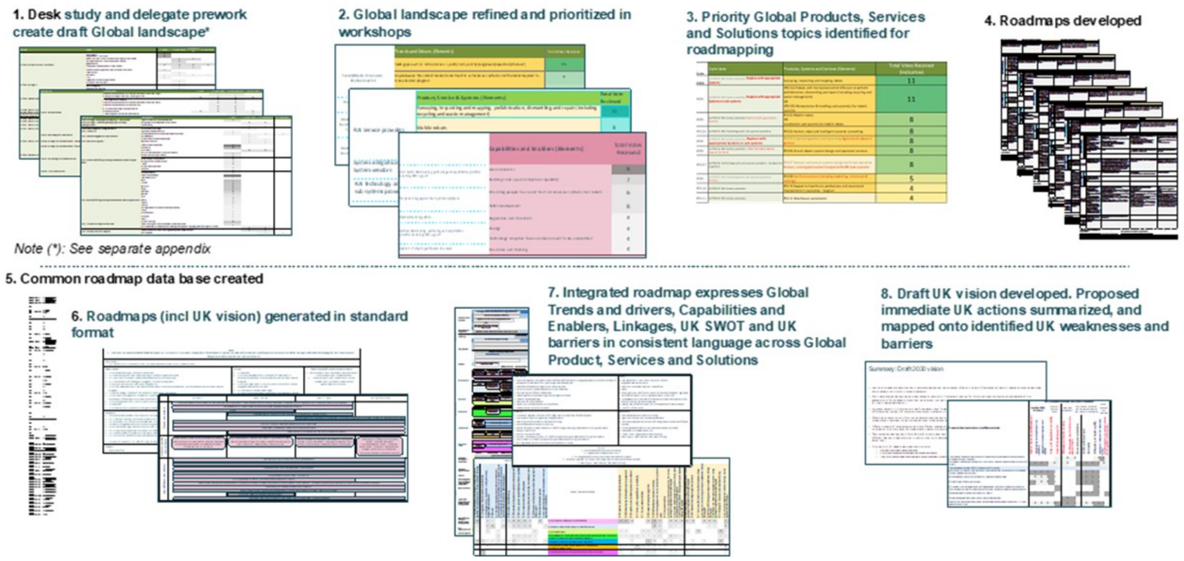



**Figure 3: Overview of the development process**

The 'trends and drivers' layer of the landscape identifies key global and national features, such as: economic; social/media; environmental; government policy and funding priorities; strategy and market/customer need which present competitive opportunities, challenges, and threats for service robotics.

The 'capabilities' layer of the landscape appraises the ability to respond to customer requirements, competitiveness challenges and value-capture opportunities. This includes, for example: enabling digital technology; strength of supply chain; sectoral and cross-sectoral funding and other support; standards and regulation; people and engagement (e.g., skills, change management); academic and other research; policy and other financial and legal factors.

The relationships discovered between trends and drivers and capabilities lead to identification of prioritised topics for roadmapping.

Figure 3 shows the sequence of activities followed, from desk study to final integrated roadmap. Note the differentiation of *global* and *UK* topics at various stages, with a gradual tightening of focus upon the latter.

# Appendix 3: Participating organisations

**ADL**
**Autonaut Ltd**
**Barrnon Limited**
**BEIS**
**BladeBUG Limited**
**BotsAndUs**
**Britbots**
**BT Group**
**Cambridge Space Associates**
**Consequential Robotics Ltd**
**Costain Group PLC – London**
**Createc**
**EPSRC**
**GMV NSL**
**Headlight AI Limited**
**Heriot-Watt University**
**HyBird Ltd**
**HydroSurv Unmanned Survey (UK) Ltd**
**Innvotek Ltd**
**KTN**
**University of Manchester**
**National Robotarium**
**Ocado**
**ORE Catapult**
**Perceptual Robotics Limited**
**Q-Bot Ltd**
**QinetiQ**
**R U Robots**
**Rolls-Royce**
**Ross Robotics Ltd**
**Rovco**
**Sellafield Ltd**
**Seyo Limited**
**Shadow Robot Company**
**Small Robot Company**
**Sonardyne**
**Tharsus Ltd**
**UK Atomic Energy Authority**
**UK Defence Solutions Centre**
**UKRI/Innovate UK**
**University of Edinburgh**

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**Institute for Manufacturing: IfM**

The IfM is part of the University of Cambridge's Department of Engineering. With a focus on manufacturing industries, the IfM creates, develops and deploys new insights into management, technology and policy. We strive to be the partner of choice for businesses and policy-makers, as they enhance manufacturing processes, systems and supply chains to deliver sustainable economic growth through productivity and innovation.

**IfM Engage**

IfM Engage is owned by the University of Cambridge. It transfers to industry the new ideas and approaches developed by researchers at the IfM. Its profits are gifted to the University to fund future research activities.

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