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ROBOTS, THEIR FUTURE AND THE ROLES FOR PUBLIC POLICY

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Abstract

This paper addresses the current and emerging uses and impacts of robots across the economy, the mid-term future of robotics and the role of policy. Progress in robotics will help to make life easier, richer and healthier. Wider robot use will help raise labour productivity. As science and engineering progress, robots will become more central to crisis response, from helping combat infectious diseases to maintaining critical infrastructure. Governments can accelerate and orient the development and uptake of socially valuable robots, for instance by: supporting cross-disciplinary R&D, facilitating research commercialisation, helping small and medium-size enterprises (SMEs) understand the opportunities for investment in robots, supporting platforms that highlight robot solutions in healthcare and other sectors, embedding robotics engineering in high school curricula, tailoring training for workers with vocational-level mechanical skills, helping SMEs participate in standards development processes, supporting data development useful to robotics, ensuring flexible regulation conducive to innovation, strengthening digital connectivity, and raising awareness of the importance of robotics.

Keywords: Digital, economy, education, employment, innovation, industry and entrepreneurship, science and technology

Synthèse

Le présent document traite de la robotisation, dans ses applications et conséquences, actuelles et en voie d'apparition, à l'échelle de toute l'économie, dans ses perspectives à moyen terme et dans le rôle des pouvoirs publics à son égard. Les progrès de la robotique contribueront à rendre la vie plus facile, plus riche et plus saine. Le déploiement des robots contribuera à accroître la productivité du travail. Avec les avancées de la science et de l'ingénierie, ceux-ci sont appelés à tenir une place centrale dans la gestion des crises, qu'il s'agisse de la lutte contre les maladies infectieuses ou du maintien en fonctionnement des infrastructures critiques. Les pouvoirs publics sont en mesure de hâter et de guider le développement et l'adoption de robots utiles à la société, par exemple en encourageant la R-D interdisciplinaire, en facilitant la commercialisation de la recherche, en aidant les petites et moyennes entreprises (PME) à comprendre les opportunités d'investissement que la robotique leur offre, en soutenant les plateformes qui promeuvent des solutions robotisées dans le secteur des soins et dans d'autres secteurs, en intégrant le génie robotique aux programmes d'enseignement secondaire, en ajustant la formation dispensée aux travailleurs qualifiés en mécanique, en favorisant la participation des PME aux processus normatifs, en agissant en faveur du développement de données utiles à la robotique, en veillant à ce que la réglementation soit souple et propice à l'innovation, en renforçant la connectivité numérique et en menant une action de sensibilisation à l'importance de la robotique.

Mots-clés : Numérique, économie, éducation, emploi, innovation, industrie et entrepreneuriat, science et technologie

Executive Summary

Progress in robotics will help to make life easier, richer and healthier. Robots are used in every part of the economy, from manufacturing to education. They come in many shapes and sizes and perform a growing number of roles: harvesting crops, accelerating laboratory research, cleaning up environmental waste, disinfecting hospital rooms, helping surgeons, exploring the oceans, and many more. As science and engineering progress, robots will also become more central to crisis response, from helping combat infectious diseases, to performing search and rescue, operating essential services such as waste treatment, and maintaining critical infrastructure such as power systems. Claims that robots will cause widespread job losses have not been borne out to date. But robots are essential to raising sluggish growth in labour productivity across advanced economies. And as robots become more capable they will help society cope with long-term challenges such as population ageing. However, the potential of robotics is only beginning to be achieved. Governments possess the policy tools to support and orient the development of socially valuable robots and increase their uptake.

Policies for progress in robotics

Publicly supported R&D is essential to progress in robotics, and research priorities are widely agreed in the robotics community. Advances in robotics requires progress in computer science, cognitive science, biology, engineering, mathematics, materials science and other fields. Cross-disciplinary research is vital. International research cooperation is valuable for all countries, given the wide diversity of robotics technologies.

Government and corporate challenge prizes have helped to advance robotics. Challenge prizes elicit R&D effort that can dwarf the value of the prize itself. They can help to identify talented individuals and teams, and draw attention to ideas that deserve a second chance. How a challenge prize is designed can affect its cost-effectiveness. Establishing a portfolio of robotics challenge prizes could help tackle a range of social goals, including combating infectious diseases. Consultation processes engaging a wide set of stakeholders can help identify the right challenges.

Testbeds for robotics – especially if equipped with a variety of robot systems - facilitate research and innovation, lower technological risk and help to speed robot uptake. Policy should aim to optimise technology commercialisation regardless of the type of technology. However, when social priorities are urgent, as during the COVID-19 pandemic, accelerating technology transfer in specific fields can help.

Institutional gaps in the process of research commercialisation can hinder progress. For example: institutions that fund health research may lack knowledge of robotics; funders of science research can lack expertise in the day-to-day of medical practice; and, new robot technology can be too commercially immature to interest venture capitalists. Good ideas might end up stranded in an institutional landscape that fails to find them. National reviews of institutions and their functions can help to identify gaps and suggest solutions. Governments can also help to selectively strengthen local concentrations of institutions and expertise, which have proven successful in health-related robotics.

Accelerating the uptake of robots

The use of industrial robots varies greatly by region, country and size of firm. An uncertain return on investment (ROI) can hinder adoption in firms. ROIs were easier to calculate for earlier generations of robot. Policy could help by providing information on expected ROIs and how they are calculated. Offsetting expenditure on robots against taxable income, or offering investment tax credits on machinery, including robots, will help. Officials running programmes to help diffuse technology should also be well informed of the many ways that small and medium-size enterprises (SMEs) can use robots. Public attitudes to robots also affect uptake and may be amenable to influence, for instance by supporting exhibitions.

Among other steps to increase robot use, governments can support platforms that highlight robot solutions in healthcare and other sectors. In a crisis, a high level of institutional familiarity with robot technologies can also increase the readiness to rapidly repurpose or innovate with currently available robots. Other crises, such as the 2011 accident at the Fukushima-Daiichi nuclear power plant, have shown the need for such readiness.

Some countries are developing new robotics curricula, even for primary-level students. Robotics engineering programmes could be embedded in high school curricula. Not all robot-related jobs are software jobs; many concern hardware. Training could help to open such jobs to workers with vocational-level mechanical skills. Many of the necessary skills do not require a four-year degree. Shorter courses can help, especially if delivered at scale.

Technical standards pervade robotics. But SMEs often struggle to access, interpret and use standards. Governments can help SMEs participate in standards development processes. Current standards for safety-related control of robots are outdated in a world in which AI-equipped robots perform safety-critical tasks.

A conducive digital eco-system for robotics

Policy can support data development useful to robotics, especially in fields such as education and healthcare, and facilitate data sharing and open data in (robotics-relevant) science. Policymakers should examine the effect on robotics of restrictions or uncertainty in collecting data for training intelligent robots, which can hinder innovation.

Regulating robotics is increasingly complex due to the speed of technical change, new robot capabilities and novel forms of human-robot interaction. An obvious concern is that robotics changes faster than regulatory frameworks. Existing laws are often adequate to legal disputes that robots can raise, but some changes may be necessary, particularly for machines that learn in the field. Robots might also raise new issues of individual privacy. For instance, the adequacy of existing privacy regulation might need to be considered if robots in a care facility or domestic setting could also gather sensitive personal data.

Regulations for some robot applications might be adjusted in response to crisis conditions. A case in point, with respect to COVID-19, is the regulation of delivery robots. These present fewer safety concerns if a population is in lockdown, and regulators might be justified in lowering liability for innovators and de-emphasising risk avoidance.

More countries should consider using regulatory sandboxes for robotics, as Singapore has done, especially in regulation-intensive fields such as healthcare. Policies and technologies that strengthen digital security also matter for safe robotics.

Autonomy levels for road vehicles exist on a scale from 1 to 5. However, for medical robots there is no equivalent. Defining autonomy levels would provide a basis for allocating different technologies to the most suitable regulatory approval procedures.

Digital connectivity, particularly 5G broadband, is increasingly important. Fibre-optic cable has characteristics critical for some robot uses. In the emerging field of remote surgery, for example, the low signal latency that fibre-optic cable provides is essential.

Résumé

Les progrès de la robotique contribueront à rendre la vie plus facile, plus riche et plus saine. Les robots sont utilisés dans chacun des domaines de l'économie, depuis l'industrie manufacturière jusqu'au secteur de l'éducation. De toutes formes et de toutes tailles, ils effectuent des tâches toujours plus variées : faire les récoltes, accélérer la recherche en laboratoire, ramasser les déchets en extérieur, désinfecter des salles d'hôpital, seconder des chirurgiens, explorer les océans, et bien d'autres encore. Avec les avancées de la science et de l'ingénierie, ils sont appelés à tenir un rôle central dans la gestion des crises, que ce soit pour lutter contre les maladies infectieuses, mener des opérations de recherche et de secours, assurer la continuité de services essentiels, comme le traitement des déchets, et maintenir en fonctionnement les infrastructures critiques, dont les systèmes d'alimentation en électricité. Les affirmations selon lesquelles leur utilsation allait entraîner de vastes destructions d'emplois n'ont pas, à ce jour, été confirmées par les faits. Les robots sont au contraire indispensables aux économies avancées pour stimuler une croissance de la productivité du travail pour l'heure léthargique. Dotés de capacités plus nombreuses, ils aideront la société à relever certains défis à long terme, comme le vieillissement démographique. Quoi qu'il en soit, le potentiel de la robotique commence seulement de se concrétiser. Les pouvoirs publics possèdent les instruments qu'il faut pour soutenir et orienter le développement de robots utiles à la société et en favoriser l'adoption.

Des mesures propres à soutenir les progrès de la robotique

Le financement public de la R-D est indispensable aux progrès de la robotique, et les priorités de la recherche dans ce domaine font largement consensus parmi les spécialistes. Ces progrès doivent prendre appui sur ceux de l'informatique, des sciences cognitives, de la biologie, de l'ingénierie, des mathématiques, de la science des matériaux et d'autres disciplines encore. La recherche interdisciplinaire est indispensable. La coopération scientifique internationale est bénéfique à tous les pays, compte tenu du vaste éventail des technologiques robotiques.

Les concours à prix, lancés par les pouvoirs publics ou les entreprises, ont contribué aux avancées de la robotique. Ils suscitent des efforts de R-D parfois sans commune mesure avec la récompense offerte. Ils peuvent aussi révéler des individus et des équipes de grand talent, et attirer l'attention sur des idées qui méritent d'être reconsidérées. Les modalités d'organisation d'un concours à prix peuvent avoir une incidence sur le rapport coût-efficacité de celui-ci. L'ouverture d'un ensemble de concours à prix dans le domaine de la robotique pourrait servir différents objectifs sociaux, dont la lutte contre les maladies infectieuses. La consultation d'un vaste éventail de parties prenantes aiderait à recenser les problèmes auxquels il est indiqué de chercher une solution par ce moyen.

Les bancs d'essai destinés aux technologies robotiques – à plus forte raison ceux équipés de différents systèmes robotiques – facilitent la recherche et l'innovation, atténuent le risque technologique et contribuent à accélérer la diffusion des robots. Les pouvoirs publics devraient prendre pour but d'optimiser la commercialisation des technologies, indépendamment de la nature de ces dernières. Cela étant, lorsque les priorités sociales se doublent d'une urgence, comme durant la pandémie de COVID-19, il peut s'avérer utile d'accélérer les transferts de technologies dans des domaines bien déterminés.

Les carences institutionnelles à l'égard du processus de commercialisation de la recherche peuvent être un frein aux avancées de cette dernière. À titre d'exemple, les institutions qui financent la recherche dans le domaine de la santé sont parfois mal renseignées au sujet de

la robotique ; il peut manquer aux bailleurs de fonds de la recherche scientifique une connaissance fine de la pratique médicale au quotidien ; les nouvelles technologies robotiques peuvent être insuffisamment matures, sur le plan commercial, pour intéresser des investisseurs en capital-risque. Les bonnes idées peuvent rester sans lendemain si elles passent inaperçues dans le paysage institutionnel. Des examens nationaux des institutions et de leur rôle peuvent aider à repérer les lacunes et à trouver le moyen d'y porter remède. Les pouvoirs publics ont aussi la possibilité de favoriser, au cas par cas, le renforcement des concentrations d'institutions et de connaissances spécialisées à l'échelon local, compte tenu des bons résultats obtenus dans le domaine de la robotique appliquée au secteur de la santé.

Intensifier le recours aux robots

L'utilisation des robots industriels varie très sensiblement selon la région, le pays et la taille des entreprises. Une rentabilisation incertaine sera de nature à freiner l'adoption de ces systèmes par ces dernières. Les retours sur investissement sont plus faciles à calculer pour les dernières générations de robots. Les pouvoirs publics pourraient intervenir à bon escient en communiquant des informations au sujet des retours escomptés et de leur mode de calcul. La déduction des investissements robotiques du revenu imposable, ou l'application d'un crédit d'impôt aux dépenses d'équipement – y compris les robots – sera une autre mesure utile. Les fonctionnaires qui animent des programmes de vulgarisation technologique devraient être au fait des nombreux usages que la robotique peut trouver dans les petites et moyennes entreprises (PME). L'opinion du public a elle aussi une incidence sur l'adoption des robots et doit pouvoir être influencée dans le bon sens, par exemple par des expositions organisées avec le concours des autorités.

Au chapitre des dispositions propres à encourager l'utilisation des robots, ajoutons que les pouvoirs publics peuvent apporter leur soutien à des plateformes en ligne servant à faire la promotion des solutions robotiques disponibles dans le secteur de la santé ou ailleurs. En période de crise, par ailleurs, une grande familiarité des institutions avec les technologies robotiques peut rendre mieux à même d'adapter les robots disponibles sur le moment, ou de leur trouver des usages novateurs, en peu de temps. D'autres crises par le passé, comme l'accident de la centrale nucléaire de Fukushima Daiichi, en 2011, ont montré combien il était important de se tenir prêt à ce genre d'éventualité.

Quelques pays ont fait une place à la robotique dans leurs programmes scolaires, dès l'école primaire pour certains. Le génie robotique pourrait être enseigné au secondaire. Tous les métiers de la robotique ne font pas nécessairement intervenir l'informatique ; nombreux sont ceux en effet qui portent sur l'aspect matériel. Une formation adéquate contribuerait à ouvrir ces emplois aux travailleurs qui ont étudié la mécanique dans le cadre de l'enseignement professionnel. Une bonne partie des compétences nécessaires, en effet, peuvent s'acquérir sans avoir à préparer un diplôme en quatre ans. Des formations plus courtes seraient bienvenues, à plus forte raison si elles sont dispensées à grande échelle.

Les normes techniques sont omniprésentes dans le domaine de la robotique. Or les PME rencontrent souvent des difficultés à les consulter, les interpréter et les utiliser. Les pouvoirs publics peuvent aider ces entreprises à participer aux processus qui conduisent à leur élaboration. Les normes en vigueur relatives aux contrôles de sécurité applicables aux robots sont totalement obsolètes à l'heure où des robots dotés d'une intelligence artificielle exécutent des tâches essentielles à la sécurité.

Un écosystème numérique propice à la robotique

Les pouvoirs publics peuvent encourager l'élaboration de données utiles à la robotique, notamment dans les domaines de l'éducation et de la santé, et faciliter le partage et l'ouverture des données scientifiques (intéressant la robotique). Il conviendrait que les responsables de la formulation des politiques étudient les effets induits par les restrictions mises à la collecte de données destinées à l'entraînement de robots intelligents, ou par l'incertitude entourant celle-ci, qui peuvent être des freins à l'innovation.

Il devient de plus en plus complexe d'encadrer la robotique du fait de la vitesse à laquelle les techniques changent, des nouvelles capacités des robots et des nouvelles formes d'interaction avec l'homme. Force est de constater en effet que la robotique évolue plus vite que les cadres réglementaires. Les lois en vigueur permettent généralement de régler les différends dont les robots peuvent être la cause, mais certains aménagements seront sans doute nécessaires, notamment pour les machines capables d'apprendre sur le tas. Les robots peuvent aussi soulever des problèmes nouveaux mettant en jeu la vie privée des individus. Ainsi, il pourrait y avoir lieu de revoir la réglementation existant en ce domaine si les robots utilisés en établissement de soins ou à domicile devaient être aussi en mesure de collecter des données personnelles sensibles.

Les dispositions applicables à certaines applications robotiques pourront être aménagées en situation de crise. Le cas des robots-livreurs, dans le contexte du COVID-19, fournit à cet égard un excellent exemple. Ces robots présentent un moindre danger si la population est confinée, aussi les régulateurs pourraient-ils légitimement abaisser la responsabilité des innovateurs et ne plus mettre autant l'accent sur la prévention des risques.

Davantage de pays devraient envisager de recourir à des bacs à sable réglementaires dans le domaine de la robotique, et suivre en cela l'exemple de Singapour, en particulier dans des domaines très réglementés comme peut l'être celui des soins de santé. Les politiques et les technologies qui renforcent la sécurité numérique concourent aussi à une robotique sans risque.

Le degré d'autonomie des véhicules automobiles est noté sur une échelle de 1 à 5. Or, il n'existe rien de semblable pour les robots médicaux. La définition de niveaux d'autonomie serait un premier pas vers l'attribution à chaque technologie d'une procédure d'approbation réglementaire appropriée.

La connectivité numérique, et en particulier la 5G haut débit, prend une importance croissante. Les câbles à fibres optiques possèdent en effet des caractéristiques absolument essentielles à certaines applications de la robotique. Ainsi en est-il, dans le domaine nouveau de la chirurgie à distance, de la faible latence du signal.

Making life easier, richer and healthier. Robots, their future and public policy

1. Introduction[1]

Robots have long excited curiosity. Mechanical automata – early precursors of robots - trace as far back as ancient Greece and 10th century BC China. Today, progress in many fields of science, technology and engineering – and especially artificial intelligence (AI) - are rapidly increasing the sophistication and diversity of robots. As this paper describes, progress in robotics is essential to making life easier, cleaner, healthier and richer. The pervasiveness of robots, what they can do, and how people interact with them, are set to change in far-reaching ways.

This paper examines:

- What robots are, and why some governments choose to give robotics strategic importance (section 2);
- Recent achievements in basic and applied robotics research (section 3), and what these imply for future robot capabilities and for public R&D priorities (section 4, with respect to robotics for healthcare, as well as section 5 and, at length, Annex 1);
- Current and future roles for robots (section 4). While spanning areas as diverse as industry, education and the oceans, this section pays particular attention to robots in healthcare, what they have contributed (and failed to contribute) to combating COVID-19, and their possible roles in addressing new disease (and other highly disruptive) threats;
- The logic, design and impacts of public policies to support robotics, widen the use of robots and maximise their social benefits (section 5).

For ease of reference, the main policy observations are summarised in box 1. Section 6 concludes.

2. Background – why robots matter

The Oxford English Dictionary defines a robot in two ways. The first definition is "a machine capable of carrying out a complex series of actions automatically, especially one programmable by a computer." By this definition smart phones are robots: they perceive something (through microphones, cameras and text input) and they act on their perceptions (putting appointments in calendars, sending money, etc.). Autonomous vehicles would also count as robots, as they have perception systems and actuators (a type of motor that converts energy into work). The second definition is "a machine resembling a human being and able to replicate certain human movements and functions automatically." This paper focuses on machines that are closer to the second definition, but also includes examples from the first definition (such as automated warehouse movers that have some autonomy but which do not resemble humans). This paper also covers machines with abilities that belong to some non-human parts of the natural world, such as insects.

[1] An earlier draft of this text was used as the basis for the chapter on robotics - "Why accelerate the development and deployment of robots?" - in the *Science, Technology and Innovation Outlook 2021*.

The sophistication and diversity of robots are rapidly increasing. Perceptions of robots as machines on assembly lines are being added to as the general public becomes familiar with systems such as robotic vehicles, vacuum cleaners and lawn mowers. Less familiar systems include intelligent laboratory robots, collaborative robots, ocean-going, space-faring, and search and rescue robots; and robot surgeons. As this paper discusses, progress in robotics has the potential to improve the quality of people's lives in many ways. However, the conceivable impact of robotics is just beginning to be realised. As the co-founder of the world's most successful consumer robotics company recently put it "…we are just about none of the way to achieving the potential of robotics…".[1]

Box 1. Main policy recommendations

Public support for robotics R&D is essential, and research priorities are widely agreed in the robotics community. Robotics requires cross-disciplinary research, obstacles to which should not hinder the field. The diversity of robotics technologies means that for all countries **international research cooperation** will be valuable. Governments can also provide policy support in ways that strengthen localised concentrations of institutions and expertise, which have proven successful in health-related robotics.

A **portfolio of robotics challenge prizes** could help to tackle a range of social goals, including combating infectious diseases. Good design practices can improve the cost-effectiveness of prizes. **Consultation processes with a wide set of stakeholders** can help identify the right challenges. **Many public agencies and parts of government can play a role** in the development of robotics, funding a wide variety of robotics.

Robotics testbeds – especially those equipped with a variety of robot systems - facilitate research and innovation, lower technological risk, and help to speed robot uptake. When social priorities are urgent, as during the COVID-19 pandemic, **accelerating technology transfer in targeted fields** can help.

Helping firms understand the returns on investments in robots is important. Officials working in programmes aimed at technology diffusion should be fully informed of the many ways that small and medium-size enterprises (SMEs) can use robots. Allowing **first year expensing, or even investment tax credits on machinery**, including robots, will help. **Public attitudes to robots** also affect uptake and may be amenable to influence, for instance by supporting exhibitions and publicising beneficial or novel uses of robots.

To facilitate robot use in health systems, governments can **support platforms that highlight leading-edge solutions**. In health systems, and in government more widely, a high level of **familiarity with robot technologies** can increase the preparedness to use diverse robot solutions in crisis situations.

Experimentation with robot-related curricula can build on evidence from countries that have already developed such curricula. Also relevant are reforms to education to **attract more students to STEM** fields and help them flourish. **Training** can open robot-related jobs for workers with vocational mechanical skills. **Short and on-line courses can help, especially if delivered at scale**.

Policy can help fund **the development of data useful to robotics and to robot adoption in public services**. Policy can also facilitate **data sharing** and **open data in (robotics-related) science**. Policymakers should examine if data policies are creating uncertainty or cost for robot development and innovation, and weigh these outcomes against other societal priorities such as privacy. **Digital connectivity**, particularly 5G broadband, is increasingly important. Wide coverage of **fibre-optic cable** will also enable some critical robot uses.

Regulation must keep pace with rapid technical change in robotics. While existing laws are often adequate, some may need to change. The major remaining legal conundrum is **the design of legal frameworks to govern machines that learn in the field. Establishing levels of autonomy for medical robots** – similar to autonomy in road vehicles - is necessary for the entire sector. **Regulations need to be easily interpreted**, which is not always the case today.

Regulations for some robot applications might be adjusted in response to crisis conditions. A case in point, with respect to the COVID-19 pandemic, is the regulation of delivery robots. These present fewer safety concerns if a population is in lockdown, and regulators might be justified in lowering liability for innovators and de-emphasizing risk avoidance. More countries should consider using **regulatory sandboxes** for robotics, especially in regulation-intensive fields such as healthcare.

Governments can facilitate **the participation of SMEs in standards processes**, and help bring their views to the attention of organisations concerned with standardisation. Open-source community-vetted platforms focused on interoperability of robot systems will help.

Policies and technologies that **strengthen digital security** are important for safe and effective robotics. **Removing unnecessary barriers to trade** also matter, as these can limit international sourcing of robot intermediates.

Robots are the most significant interface between AI and the physical world. Developments in both fields have been deeply inter-connected. For example, an early goal of machine vision research was better robot navigation; in turn, robots served as platforms for demonstrating more capable AI. Some scientists hold that robots provide the best setting for tackling some major goals in AI research. They argue that by using AI in machines with human-like form, research is more likely to find how to create AI with human attributes such as "common sense". At a minimum, the "Moravec paradox"[2] - the observation that robots do many things easily that humans find difficult, and *vice versa* - has prompted researchers to explore the distinctive features of human and machine abilities. Beyond research, it is also through the actions of robotic systems that many questions in the governance of AI will arise and require solutions.

Robots also have a unique place in the public imagination. Humans react differently to objects in physical space than to objects on screens. People unconsciously treat robots as if they were human (Fussell *et al*., 2008).[3] Youtube clips of Boston Dynamic's *Atlas* robot performing backflips and appearing eerily human went viral.[4] In 2015, MIT demonstrated the quadruped robot "Cheetah" leaping untethered over obstacles at 23 kilometres per hour. Here again, the images were unprecedented and arrestingly life-like.[5]

Robots are not a technology as such (although this paper often refers to 'robot technology' for brevity). They are combinations of technologies, some of which are advancing faster than others. The building blocks of progress in robotics are many and include developments in sensors, such as laser systems with improved range and angle resolution; intelligent control, such as systems that orchestrate a robot's actions via statistical predictions of future conditions; actuators, such as dexterous grippers (figure 1); and, haptic technologies, which give operators the perception of sensing what a robot is touching, and even how it is balanced.

Progress in manufacturing technology such as laser sintering (a form of 3D printing) lowers cost and makes it possible to build more capabilities into robots. The proliferation of robot types and abilities also comes from advances in basic and applied science. Biomechanics, biology, cognitive science, computer science, materials science, neuroscience and mathematics are just some of the relevant fields. Emerging disciplines, such as computational psychiatry, will contribute in new ways.[6] Robots have even become tools of basic science in their own right. For instance, research on robots is helping to better understand how humans walk, and how bio-mechanical subsystems are integrated.

Figure 1. Robot grippers are increasingly dexterous and intelligent

With permission: SCHUNK corporation

Robots are also the focus of popular and academic concerns about the future of work, with views spanning a gamut from optimism to extreme pessimism. This paper briefly highlights recent research which suggests that robots make positive contributions to employment over time, but with varying implications across groups of workers. New collaborative robots are described in section 4 that enable mixed human-robot teams to outperform teams of only robots or only humans. The potential for optimising robot-worker collaboration using AI is also considered. Such developments raise the possibility that leading-edge robot technologies could have different impacts on labour markets than previous systems.

Robotics sits at the centre of many topics in science and technology policy. How robotics develops, and the impacts it has, will be shaped by policies towards such diverse issues as basic and applied R&D, research commercialisation, taxation, public-private partnerships, technology diffusion, legal and regulatory frameworks, technical standards, and digital connectivity and security. Indeed, many notable recent advances in robotics trace directly to the effects of public policy, such as the challenge prizes run by the Defense Advanced Research Projects Agency (DARPA) and the National Aeronautics and Space Administration (NASA) in the United States.

Robots as a strategic technology

Some governments now give strategic importance to robotics. Although national priorities vary, a common goal is to secure the contribution of robots to competitiveness. Because they are faster, stronger, more precise and consistent than workers, robots have raised productivity in important parts of the economy such as the automotive industry (Box 2). They will do so again in an expanding range of sectors and processes. Furthermore, new generations of miniaturised, complex products with short life cycles will require levels of adaptable assembly, precision and reliability that exceed human capabilities. Progress in robotics also creates global market opportunities, which some countries aim to supply.

Box 2. Robots and productivity

Rates of productivity growth in advanced economies continue to lag. The adoption of robots is already contributing to improved productivity, at the level of individual business processes, firms, industries and the economy overall.

Numerous studies show that manufacturers that use robots are more productive than non-users (e.g., Fraunhofer [2015]; Koch, Manuylov and Smolka [2019]; and Dixon, Hong and Wu [2020]).

At a country level, Dauth *et al*., (2017) found that robot adoption in Germany led to a GDP increase of 0.5 percent per person per robot between 2004 and 2014.

Graetz and Michael (2015) provide the most detailed cross-country assessment to date of the aggregate productivity effects of robots across advanced economies. Examining 14 industries across 17 countries over the period 1993-2007, they found that industrial robots significantly increased labor productivity and value added. A 2018 paper, by the same authors, again using a panel of industry data across 17 countries, showed that investment in robots accounted for around 15 percent of economy-wide productivity growth between 1993 and 2007. Similar results were found in a cross-country study by Kromann, Skaksen and Sørensen (2011).

In addition to effects on productivity, Liu *et al.*, (2020), examined sector level data in the People's Republic of China (hereafter "China") and found that the use of robots leads to wider technological innovation by increasing knowledge creation and technology spillovers.

An important finding comes from Stibale, Suedekum and Woessner (2020) who studied of industrial robots across six European countries from 2004 to 2013. They showed that robots dis-proportionally raise productivity in firms that are most productive to begin with (and, generally, larger). This work, as well as other research showing that robot adoption is concentrated among larger firms (Humlum, 2019), underscore the importance of policies to accelerate uptake of robots and other productivity-raising technologies across a broader spectrum of the enterprise population (see Section 5, "Robots and public policy").

With such strategic considerations in mind, alarm is often expressed when leading robotics companies pass into foreign ownership, along with their intellectual property and know-how. Such concerns are explicit in a number of national robotics strategies, like those of Japan and the United States. China is perhaps preeminent in terms of national strategic ambition in robotics (Box 3).

Box 3. China's development of a world-class robotics industry

No country is more active than China in developing an advanced robotics industry. China has acquired many robotics companies abroad with support from central and provincial governments. The acquisitions have often been esteemed German and Italian robot manufacturers and integrators (i.e. companies that assist other firms to deploy robots). Examples include the Chinese fund AGIC's purchase of Italian robotics company Gimatic in 2016. Germany's robot integrator KraussMaffei, acquired in 2016 by a consortium led by the state-owned China National Chemical Corporation. A

German producer of robot welding guns, Nimak, bought in 2019, and the jewel in the crown of European robot manufacturers, Germany's Kuka AG, acquired in 2016 by China's home appliance maker, Midea. Among other reactions, the latter purchase led the IG Metall trade union to seek alternative buyers (without success). Further afield, Chinese interests have purchased HTI Cybernetics, Paslin, and Xperception, in the United States, and Sweden's Robot System Products.

China's National Development Plan for Robotics (2016-20) announced the goal of developing a domestic industrial robots sector that is technically equal to the leading international competitors, and supplying at least 45% of the domestic market (Ministry of Industry and Information Technology, 2015). Expanding production of robots for seniors and medical care is a further aim.

A national robotics roadmap was prepared after publication of *Made in China 2025* (a national initiative for advanced manufacturing). The roadmap identified key technologies and components for industrial and service robots, as well as opportunities to strengthen co-ordination between research and application, along with initiatives for standardisation, quality assessment and certification. In 2016 China announced a robot certification scheme and issued the first certificates.

Compared to countries such as Japan and South Korea, robot density in China is low. However, Chinese regions with strengths in manufacturing mechanical and electrical products, such as the southeast provinces, have initiated large-scale programmes titled "Robots Replace Humans". Many provincial governments also subsidise firms that invest in robots.

3. Emerging robot capabilities

This section reviews a number of recent developments in robotics. Many of these are research achievements, or prototypes, which may be years from commercial use. Others are just beginning to find commercial application. However, these advances suggest some of the new roles and capabilities that robots will have in the near future. The description of recent developments in this section also provides context for the discussions of public research priorities in section 4 (with respect to robotics for healthcare), section 5 and, at length, Annex 1.

Soft robotics

Until recently robots were physically rigid. Advances in fields such as materials science, actuators, sensing and modelling have produced an emerging class of deformable and compliant robots that can squeeze, stretch, climb, change shape and self-heal (Terryn et al., 2017). Research on soft robotics aims to amplify abilities to grow, evolve, self-repair and biodegrade (Laschi, Mazzolai and Cianchettiet, 2016). Another goal is to use the property of softness itself to lower the risk of harm from physical interaction with robots. Inspiration for many developments in soft robotics comes from the natural world (Box 4).

Box 4. Bio-mimicry and robotics

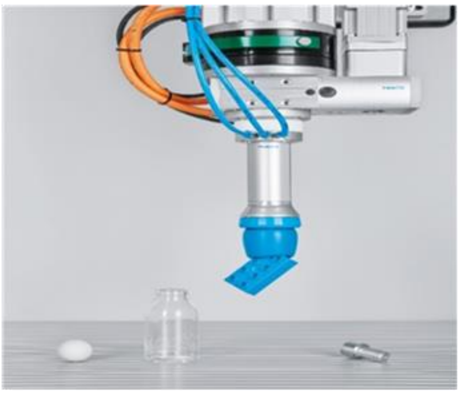
While the history of modern robotics is decades long, nature's designs are the result of hundreds, even millions, of generations of trial and error. Engineers are learning from nature's templates, terrestrial, airborne and aquatic. The African bush elephants' trunk has two extremities or "fingers" which can grasp and manipulate small and fragile objects of varying weights in dry or wet conditions. Europe's PROBISCIS project aims to mimic this achievement and define a universal system of robot manipulation.

Chameleons hunt with a uniquely adaptive tongue: as the tongue approaches an insect its edges extend and envelope the prey no matter its shape or size. Festo, a German company, built a flexible robot gripper based on this model (figure 2). Such a gripper might improve prosthetic devices.

Italy's Technology Institute, a leader in soft robotics, is designing systems that grow and move using plant-like tendrils (figure 3). Soft robotics has also yielded artificial muscles like those of the robot bee in figure 4. Should this robot crash, the muscles and wings will deform instead of breaking (Chen *et al*., 2019).

Harvard and MIT roboticists discovered that the bodies of rainbow trout enable them to swim against a current even when dead (Beal, *et al*., 2006), a finding which could have applications in energy efficiency for water-borne devices.

Figure 2. Modelled on the chameleon tongue, Festo's FlexShapeGripper uses a pliant silicone membrane to grip irregularly-shaped objects



Source: Festo.com

Figure 3. Soft robots can mimic the structures and movement of plants

With permission: Istituto Italiano di Tecnologia.

Figure 4. A prototype robot bee uses pliable muscles and wings

With permission: MIT

Miniaturisation

Since Gordon Moore published on the trend in 1965, exponential shrinking of transistors has made miniaturisation a hallmark of the digital era. Together with advanced fabrication, "Moore's Law" has helped engineers build ever smaller robots, of which the micro-robots in figure 5 are examples. Researchers at MIT recently built self-powered robots the size of a human cell. These robots are able to follow pre-programmed instructions, and record and store data about their environment that can be downloaded once a task is completed. While currently at the laboratory stage, these robots have potential uses in medical diagnostics and industry (Chandler, 2018). Biological science is also driving miniaturisation. Bacteria-powered systems already exist for drug delivery (section 4), and living robots have recently been demonstrated that assemble themselves from stem cells (Blackiston *et al.*, 2021).

Figure 5. Two Harvard Ambulatory Micro-robots developed in 2020, next to a US penny and an earlier model

With permission: Kaushik Jayaram/University of Colorado Boulder

AI and the expanding range of robot capabilities

In the late 1990s most robots possessed only insect-grade intelligence. Today, progress in AI, particularly machine learning, is revolutionising robotics. Combined with other innovations, AI is giving robots a myriad of new capabilities. This section describes some of the main developments.

Better vision

Robot autonomy relies in part on machine vision. Google researchers recently trained an AI on thousands of YouTube videos of the "mannequin challenge", in which participants imitate a stationary mannequin while filmed by a roving camera. From this footage, the AI learned to better judge depth, which could help robots to navigate unfamiliar spaces (Hao, 2019). Another breakthrough involves an algorithm that identifies partially hidden objects in chaotic scenes, which could help robots to sort unorganised objects ranging from earthquake debris to fruits for harvest (Chu, 2019).

Learning transfer across robots

AI can help robots learn from each other. A system in which robots share what they learn is more effective and efficient: all the robots can avoid a mistake made by one robot, for instance. Some disinfection robots learn the layout of hospital rooms and communicate this to companion robots. *RoboEarth* even helps robots share knowledge worldwide on an online database.

A more complex capability in robots is a group behaviour known as 'swarming'. Among social insects, such as ants, collective intelligence often surpasses individual intelligence (no individual ant has a blueprint for a colony's nest, for example). In a similar way, swarming allows groups of simple low-cost robots to generate highly complex – even hard-to-predict - behaviour. However, swarming requires AI and sensors to exchange information between each robot in the swarm. It also requires the ability of every robot to act both independently and as part of the swarm. Research on robot swarming currently focuses on drone technology. Challenges exist in modelling swarms, but there is much to gain from success: small robots are often easier to manufacture and transport than a single large robot, and they can operate in some environments that larger machines cannot.

Learning in virtual environments

Many fine sensorimotor tasks that humans perform – such as stitching a surgical incision – require periods of specialised learning, preceded by years of neurological development (from childhood to adulthood). By contrast, AI-enabled robots can learn in virtual environments using simulated experience. This saves money and time: using huge numbers of simulations, learning might take hours instead of months. In addition, mistakes can happen without the risk of real-world consequences, just as when pilots use flight simulators. New ways to create simulations are emerging. 3D scanners can capture the dimensions of real objects in a field of view, such as a factory floor, after which robots learn from the virtual version of that setting. One leading roboticist foresees a process of learning from imagination: robots would simulate and examine future circumstances, and learn from people using, among other things, the sum of visually recorded human activity available online (Pratt, 2015).

How best to bridge the gap between simulated and real environments is a subject of ongoing research. Differences between synthetic and real data can be a serious problem for AI. For example, widely publicised mistakes have resulted from medical image detection systems trained on faulty synthetic data. Another challenge is that AI programmes might successfully perform tasks in virtual environments by learning to exploit flaws in simulated data. How they do this could be unknowable to engineers and impossible (or dangerous) to replicate in a real-world environment (Bousmalis, 2017).

Learning by doing

AI is helping robots to learn by doing (and failing) in the real world, rather than following pre-programmed instructions. In the wild, newborns in many species learn to walk in minutes. This ability inspired researchers at the University of Southern California to develop an AI-controlled prosthetic leg that teaches itself to walk. The limb can master walking tasks on unfamiliar surfaces after only minutes of unstructured play. It can even be tripped and recover before the next step. The technology has many potential uses, from prosthetics that actively assist the disabled, to robots that explore uneven or changing terrain (Marjaninejad, 2019). A four-legged robot learned to walk in around two hours based on similar research (Wiggers, 2018).

Learning by curiosity

Researchers are developing robots equipped with curiosity algorithms that seek out problems and their solutions (Gottlieb *et al.*, 2013). Oudeyer (2015) shows how the behaviour of such robots can self-organize and become progressively more complex, with new cognitive stages appearing that were not pre-programmed. For example, a robot might progress from learning to walk, to predicting how to touch objects, to exploring vocal interaction. Curiosity algorithms developed by Pierre-Yves Oudeyer and his team in Paris have been used in the Sony Aibo and Qrio humanoid entertainment robots. Such robots are also serving as tools for research into human curiosity.

Object manipulation

One of the major challenges of robotics is how to grip objects of different sizes, shapes and weights, without dropping or damaging them. Error rates must be extremely low as faulty manipulation might harm persons, damage objects or disrupt systems. The challenge of manipulation is not just physical. It also concerns the intelligence needed to behave appropriately with a grasped object. For example, it is obvious to humans, but not yet to robots, that an object might have to be treated differently depending on whether it is hot or cold.

One recent advance in grasping technology involves a neural network (Dex-Net) that learns to pick up objects. Dex-Net can generalize from an object it has already seen to one it hasn't, and can decide to nudge an object to see how it should be grasped. Using Dex-Net, a different neural network can control each arm of a robot, each of which, in turn, might have a different gripping system. The developers also created a performance metric for robots specialised in picking up objects, namely "mean picks per hour". This multiplies the average time per pick by the average probability of success. Humans are capable of between 400 and 600 mean picks per hour. A machine using Dex-Net reaches 200 to 300, and could converge on human performance in a few years (Knight, 2018). Developing comparative metrics of robot and human performance could also help to forecast the impact of robots on labour markets (Box 5).

Much of the learning needed for object manipulation uses visual data, which is often abundant. A team at MIT is approaching the challenge in a different way. A person is asked to manipulate a variety of objects while wearing a glove covered in hundreds of sensors. As the person grasps and manipulates each object, a neural network learns the unique tactile patterns the objects create on the gloved hand. This technique goes some way to generating the large datasets needed for learning tactile-based grasping (Sundaram, 2019).

Box 5. Assessing the impacts of AI and robotics on skills demand and educational requirements

In recent years, public discussion of the impact of AI and robots on work has increased. However, there has been little progress in evidence-based understanding of how disruptive the changes in the workplace could become.

To explore this question, the OECD created a novel way of comparing AI and robot abilities with human abilities in literacy and numeracy. This work asked a group of computer scientists to analyse the literacy and numeracy questions that humans responded to in the OECD Survey of Adult Skills (PIAAC) and to consider whether current AI techniques could answer the same questions. PIAAC provides results for a sample of working age adults - statistically representative of 815 million adults - from 33 countries.

This unique comparative assessment showed that only 13% of workers in OECD countries have proficiency in literacy and numeracy that clearly exceeds current AI systems (Elliott, 2017). However, because no job requires only these two skills, a more complete basis for forecasting how AI and robots will affect work and the demand for skills requires comparisons across a broader range of skills. These include, for example, expert reasoning and problem solving in specialised domains, and social interaction, as well as physical abilities such as visual perception and precise motor control.

To this end, a new OECD project, the *Future of Skills*, aims to develop a comprehensive approach to evaluating how AI and robotics will transform skills demand and educational requirements. The project will provide an evidence base – a set of objective comparative measures of capability – for these technologies. Such evidence is currently unavailable for policy makers.

The project brings together computer scientists, psychologists, testing experts and educators (the latter to help understand what is possible in improving human proficiencies). The development of a comparative assessment for AI and robot abilities will involve the following steps:

- Creating a suitable taxonomy of skills that spans the full range of workplace skills. This taxonomy must identify skills that are easy for humans (like visual perception or common sense) in addition to those that are difficult, because the skills that are easy for humans may be hard for AI and robots.
- Identifying tests that can assess AI and robot capabilities in order to compare these with human capabilities. These tests must involve realistic tasks to indicate whether AI and robotics can be applied to real-world problems where the capabilities in question are needed.
- Developing an approach to sample and synthesise the judgments of AI and robotics experts about the abilities of AI and robots to perform the tasks on the tests. This approach will need to include a fully representative range of views on AI and robotics—reflecting the opinions of researchers from different countries, research traditions, subfields of expertise, and both academia and industry—and identify the true level of consensus in the field.
- The developmental work, taking place in the OECD's Centre for Educational Research and Innovation, is expected to last through the 2023-24 biennium. It will include the design of the methodology and a first systematic assessment of AI and robotics capabilities across a comprehensive set of major skill areas. After completion of this first assessment, the project is expected to become an ongoing programme that provides updates every 2-5 years on AI and robot capabilities and their implications.

Sources: Elliott (2018) and Elliott (2017).

Emotional awareness

A subfield of AI is concerned with identifying emotions. Only a small percentage of interpersonal communication conveys logical meaning. Emotion-reading systems promise radically new uses for machines. OrShea *et al.* (2018) report that the EU's iborder project has partially automated deception detection by observing a person's micro-gestures. EmoNet is a deep neural network that can classify almost any facial expression into one of eleven emotional categories (Daws, 2019). If embodied in robots, emotion-detecting AI could have uses from education to healthcare (section 4), to almost any environment where machines and people work together. For example, a new AI system associates emotional state with skeletal gait, helping robots decide how much physical distance to keep from a person (Simon, 2020).

Research needs to consolidate the theoretical underpinnings of this field. AI practitioners may have eagerly embraced a theory of micro-expressions that many psychologists are cooling to (Barrett *et al*., 2019). Among other objections, facial expressions don't map neatly onto emotional categories: a frown of anger might look like a frown of concentration. Nor do all people display or recognise emotions in the same way (Fischer, 2013).

Achieving social awareness, as distinct from emotional awareness, is a goal of many roboticists trying to develop socially interactive systems. However, emotional awareness and social awareness differ in important ways, e.g. people simply do not emote much in many of the settings in which humans interact with robots today (for example on factory floors), or may interact with them in future (for instance giving feedback to surgeons).[7]

Collaborative robots (cobots)

The ability for robots and humans to collaborate – adaptively, across changing roles, and in teams - is growing thanks to the integration in single systems of many of the technologies previously described (figure 6). Cobots are still a small fraction of all installed robot systems, but demand is set to grow as they are attached to self-driving platforms that easily traverse industrial or other work spaces (International Federation of Robotics [IFR], 2019). Developing collaborative systems is a priority for many companies and researchers, and is the centrepiece of the United States' National Robotics Initiative 2.0 (Box 6).

Box 6. Collaborative robots and the United States' National Robotics Initiative (NRI) 2.0

The focus of the NRI-2.0 programme is the integration of cobots to assist humans in every aspect of life. Multiple agencies of the federal government support the NRI-2.0 programme, including the National Science Foundation (NSF), the Department of Agriculture, NASA, and the National Institute for Occupational Safety and Health.

The programme has four main research themes: scalability, customizability, barriers to entry, and societal impact. Topics addressing scalability include: how robots can collaborate effectively with many more humans or robots than is currently possible; how robots can perceive, plan, act and learn in uncertain, real-world environments, especially in a distributed fashion; and, how to facilitate large-scale, safe, robust and reliable use of robots in complex environments. Research on customizability includes: enabling cobots to adapt to tasks, environments or people with minimal modification to hardware and software; personalizing robot interactions with people; and, improving verbal and non-verbal communication with humans. Work to lower barriers to entry focuses on fundamental and applied robotics research. This may include development of open-source cobot hardware and software, as well as testbeds (which provide specialised, controlled but realistic environments where new technologies can be tested). Work on societal impact includes: research to incorporate robotics into educational curricula; upskilling the robotics workforce; and, exploring the social, economic, ethical, security and legal implications of ubiquitous collaborative robots.

Source: NSF programme description, with slight modifications.

Figure 6. A collaborative robot assists a human operator

At another workstation such a robot might be reconfigured for other tasks

With permission: Universal Robots.

Researchers have recently begun to explore the possibility of using AI for automating the design not only of robot bodies, but also, at the same time, their constituent materials, components and main engineering features. Researchers envisage a medium-term future in which AIs can quickly evolve specialised robots to address emerging needs in niche environments. The main roadblocks to realising this possibility, and how they may be overcome, is discussed in Howard *et al.*, (2019.

In addition to the developments described above, the robotics field has also benefitted from the open source Robot Operating System (ROS), a set of software libraries and developer tools to help build robot projects and applications.

4. Current and emerging uses of robots

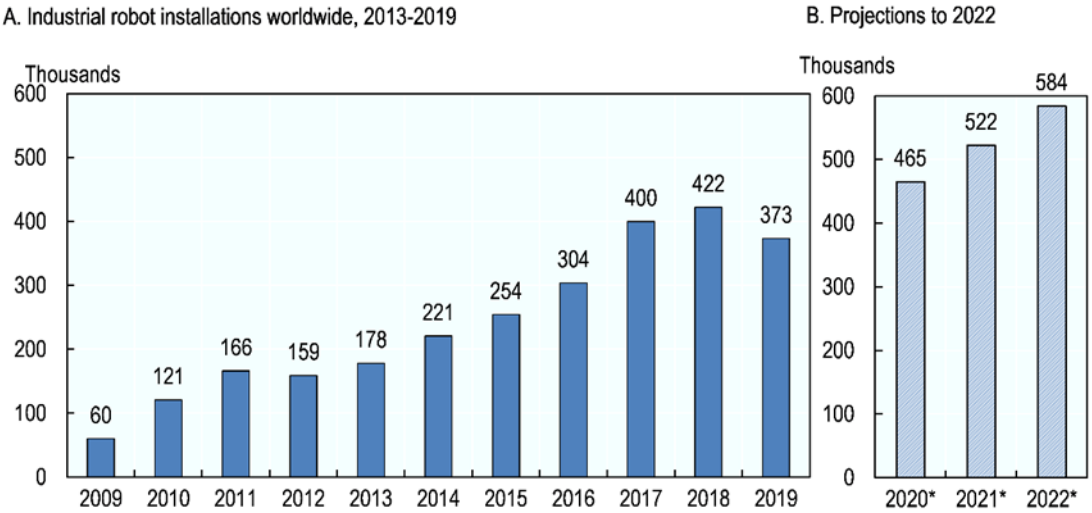
This section reviews the main current and emerging uses of robots. These include uses in industry, agriculture and services, as well as space, the oceans, and education. Owing to the COVID-19 pandemic, and the potential for robots to ameliorate this or future contagions, particular attention is given to robots in healthcare.

Robots in industry

Global sales of industrial robots have risen rapidly for many years. Around 373 000 industrial robots were sold in 2019, up 621% from 2009. Total annual sales of industrial robots could rise to 584 000 by 2022 (figure 7). A recent survey of 50 000 manufacturers in the United States found that robots have begun to be used in most sectors of industry (Miranda and Seamans, 2020). Internationally, industrial robots are most prevalent in the automotive sector, along with machinery, equipment and electronics assembly, and metals, plastics and rubber manufacturing.

Rising demand for industrial robots has a number of drivers. The next generation of miniaturized, complex products with short life-cycles will require a level of assembly adaptability, precision and reliability which exceeds human capabilities (CCC/CRA, 2016). Robots lower error rates and increase consistency and precision, e.g. when handling small fragile parts in electronics assembly. They reduce lead times for finished manufactured goods, allowing greater responsiveness to changes in retail demand. Rapid technological change – particularly in electronics - halved the price of industrial robots between 1990 and 2005 (Graetz and Michaels, 2016). New robot capabilities and greater connectivity (such as cloud computing interfaces) have opened new opportunities for use. And numerous studies show that manufacturers and other firms that use robots are more productive than non-users (see Box 2). Robots also increase worker safety in a number of ways. For example, they can replace workers in hazardous industrial environments such as foundries, and perform tasks that involve high risk of injury, such as carrying heavy loads. Indeed, in the United States, Gunadi and Ryu (2021) found that a 10% increase in robots per 1000 workers is associated with an approximately 10% reduction in the share of low-skilled individuals reporting poor health. This was largely due to the reallocation of workers to lower-risk tasks.

Figure 7. Industrial robot installations worldwide, 2009-2019, and projections to 2022



Source: Panel A. IFR (2019), *World Robotics Report 2019*. Panel B. IFR (2020), *World Robotics Report 2020.*

Can newer industrial robots help SMEs to automate?

In all countries, most manufacturers are SMEs. SMEs work exclusively with "small series manufacturing" (production runs yielding few units). This results in uneven and low utilization of machines, which reduces profitability. Most SMEs in manufacturing use manually operated machines. While many SMEs wish to automate, it is difficult to do so profitably when product volumes and product types change frequently and robots are fixed (i.e. anchored to a factory floor). Costs also increase if, under such varying conditions, robots have to be repeatedly reprogrammed. Fixed robots typically use fences for worker safety. However, in terms of efficiency alone, fences can create problems if small series manufacturing means that robots need frequent retooling. All of the above factors have led to extremely low automation rates among SMEs in manufacturing, perhaps less than 1% (or around 10 robots per 10 000 employees, compared to 1 100 to 1 400 robots per 10 000 employees in the automotive sector).

Because many customers want greater freedom of choice over product configurations, and global competition is intense, the need for more flexible and future-proof automation is also felt by large manufacturers. For example, in the automotive, electronics and white goods industries, a growing number of large firms have shortened production runs and expanded product mixes. Some large firms have also found themselves locked into the use of traditional fixed robot units with fences, with difficulties to adapt these for new products or to change factory layouts. All of these conditions raise demand for more flexible and future-proof robot solutions. In this connection, firms in many industries have five common needs:

- *Rapid robot integration and installation,* reduced from weeks to days, to speed conversion and avoid lost production.
- *Rapid production scale-up and scale-down,* to more quickly amortise investments and adjust production volumes.
- *Flexible robot configurations and fast programming,* to adjust production processes quickly to new products, and to mix products on the same machine.
- *Easily changed layout without fences*, to quickly move production lines and avoid being locked into a given factory layout.
- *Future-proofed and standardised robot solutions*, to be able to reuse robots easily as product mixes change, employing flexible but standardised solutions. Mobile robots help to provide such flexibility.

Table 1. describes the three generations of industrial robot to date. Each generation has emerged to help address the evolving needs of industry described above

Table 1. Three generations of industrial robot

Fixed robots	Collaborative robots	Flexible mobile robots
First entered industry in the 1960s, initially in the automotive sector.	First sold in 2008 (by Universal Robots).	Developed more recently.
They are large, expensive, operate from static positions indoors, have fences, require traditional programming and perform one or a small number of repetitive and sometimes hazardous tasks, such as welding and machining.	They are smaller, less expensive, more autonomous, flexible and cooperative than fixed robots. Many have low- to no-code requirements and can be programmed and used by non-specialists. Some can even imitate human counterparts. They have partly fenceless safety.	They are mobile, with automated guidance. They have fenceless safety and can handle high payloads at high speeds. They have a degree of self-programming, as well as long reach and flexible gripper solutions.
Fixed robots operate at high speed with large payloads and long reach.	Among other companies, Kuka makes collaborative robots that automatically adjust their actions to fit the next unfinished product (Lorentz et al., 2015). See also figure 6. However, collaborative robots handle low payloads, at low speeds, and have a short reach.	Figure 8 shows an example of a flexible mobile robot.

Source: Boesl and Liepert, B. (2016) and insights provided by Johan Frisk.

Figure 8. A mobile flexible OpiFlex robot, here producing COVID-19 vaccine equipment

With permission: OpiFlex.

Industrial robots and jobs

Automation and its effects on workers is the subject of a large academic and popular literature, which this paper does not aim to assess. However, it is relevant to note that industrial robots, especially the more recent models, differ in important ways from other types of automation, such as computer numerical control systems. For instance, they can be reprogrammed and flexibly applied to diverse tasks. Atkinson (2019) reviews the robot-specific research. He shows that many firm-level studies find only limited job destruction, or loss of total hours worked, attributable to robots (despite their positive effect on labour productivity - see Box 2). Some studies report significant increases in manufacturing employment a few years after investments in robots, often because of increased product demand. Where industrial robots are shown to have reduced hours worked, this often applies primarily to low-skilled workers; the declines are less pronounced for workers with mid-level skills. In addition, in some countries, especially in economic upswings, investment in industrial robots is a response to labour shortages and the demand for higher-quality output.

More recent research bears out the findings reported in Atkinson (2019). Dixon, Hong and Wu (2020) show that in Canadian firms, between 2000 and 2015, robot use was associated with increased overall employment. However, employment in managerial roles fell substantially, while rising in non-managerial roles. This contrasts with many studies on other digital technologies which have found managerial jobs harder to replace than non-managerial positions. The authors conjecture that robots may reduce the need for managers because they make fewer errors in production, and therefore need less supervision. Robots may also lower managerial employment because they reduce middle-skilled jobs while increasing low-skilled and high-skilled jobs; research suggests that low-skilled and high-skilled jobs require less managerial oversight. Dixon, Hong and Wu (2020) also show that firms' main motivation for adopting robots was not to reduce labour costs, but rather to increase the quality of products and services.

A further counter to a job-destroying view of industrial robots is that in many countries where industrial robot use is low, such as the United Kingdom and the United States, the share of manufacturing jobs in total employment has fallen rapidly in recent decades. However, this trend is much less marked in many countries with higher robot densities, such as South Korea and Germany. Similarly, countries with high rates of increase in the number of manufacturing robots (such as Sweden) have often been more successful in retaining manufacturing jobs than countries with lower rates of increase (such as the United Kingdom).

New symbioses between industrial robots and workers

The employment effects of some new types of robot might also differ from previous systems, due to their greater inter-dependence with workers. In the automotive sector, teams of robots and humans working together can be more productive than either workers or robots alone (Shah *et al*., 2011). In one study, idle time among workers in a robot-human team fell by 85% when a robot helped to coordinate the team (Unhelkar *et al*., 2018).

Paschkewitz and Patt (2020) argue that AI could optimise inter-dependence and complementarity between workers and robots. The authors begin by explaining the difficulties of optimally allocating workers and machines to different jobs. Most knowledge work does not involve neatly compartmentalised tasks with unambiguous measures of performance. Moreover, workers possess an enormous variety of skills, and the skills relevant to even a single job description can vary greatly. For instance, being detail-oriented and being creative could both contribute to the successful performance of some jobs. Accordingly, Paschkewitz and Patt conjecture that "it may never be possible to design a single human-machine interaction framework that equally suits all humans or that replaces or exceeds all types of human intelligence". However, AI is beginning to make possible a symbiosis in which robots learn from workers, and the productivity of workers increases through interaction with AI-enabled robots. The authors developed a tool, called Pivotal, to apply these ideas to warehouse robots, and describe the results as follows:

> "…the exact way to complete a task like filling an order could evolve from day to day. Workers often ended up finding variety in their jobs, handling unusual tasks such as catching a stray bird, clearing obstacles, and applying their abstract problem-solving skills to understanding why a box had two conflicting labels and deciding which one was right. Robots tended to settle into repeatable patterns with gradual performance improvement until their engineers analyzed the data and pushed out new features. This entire operation was implemented using a data-driven framework, so that machine learning could benefit from human insights and human training of AI algorithms, and humans could analyze the unexpected behaviors and emerging patterns and innovate—both on the shop floor and in the engineering office."

Paschkewitz and Patt provide technical support to *Agile Teams*[8], a DARPA project to explore how AI can mediate between knowledge workers and AI systems, tailoring tasks to individual workers and improving work processes overall, e.g. making a workplace more resilient if a worker is unexpectedly absent. In one scenario, *Agile Teams* responded to an unexpected need to deliver personal protective equipment by creating a new *ad hoc* team to complement workers already delivering regular cargo, established a new drone fleet and warehousing approach. It is currently an open question how advances that permit deeper interaction between machines and workers will affect labour market outcomes overall.

Industrial robots and firm location

The effect of robots on where firms choose to locate is as yet unclear. Fraunhofer (2015) reports that European manufacturers that use robots are less likely to relocate production outside Europe. Other analysis suggests that each additional robot per 1,000 manufacturing workers is associated with a 3.5 percent increase in reshoring (Kren *et al*., 2018). However, investments in robots have not caused reshoring of past foreign direct investment or international reallocation of resources within multi-national companies (De Backer and Flaig, 2017). Robots have so far had only small effects on participation and upgrading in global value chains, and these have mainly been in developed economies (De Backer *et al.*, 2018).

Automation might also undermine labour-cost advantages in emerging economies. Labour-intensive industries such as footwear and apparel have long provided developing countries a first rung on the ladder to industrialisation. These industries involve hard-to-automate processes requiring considerable dexterity, such as stitching difficult-to-manipulate pliable fabrics. But Adidas has now built a shoe manufacturing facility in Germany that uses a so-called ‘robot cobbler’. Fully automated, this technology permits significant customisation and takes just five hours for a full production cycle, compared to a norm of several weeks (Shotter and Whipp, 2016). Furthermore, pattern-detecting AI might soon automate inspection of the quality of a fabric’s weave. Foxconn’s decision to invest massively in robots in its Chinese plants may presage a wider trend (Brunner, 2014).

Robots in agriculture

Agricultural robots could become increasingly important in OECD countries because of the declining share of young people in the population and the physical demands of some agricultural tasks, especially in harvesting. In a recent breakthrough, researchers at the University of Cambridge developed an AI-driven robot that can identify and harvest lettuce (Hariday, 2019). Interconnected swarms of robots have managed to map and analyse every tree and piece of fruit in an orchard, generating information to improve yields and water management. The *FarmView* project, at Carnegie Mellon University, created a robot that measures the sugar content of grapes using computer vision. It drives up and down rows of grapes, picking them one-by-one when their sugar content is ideal for wine-making (Rogers, 2017). The growth of roots crops has also been predicted using drone-gathered imagery and AI (CIAT, 2020). An experimental quadruped robot has even herded sheep in a remote part of New Zealand (Hariday, 2020).

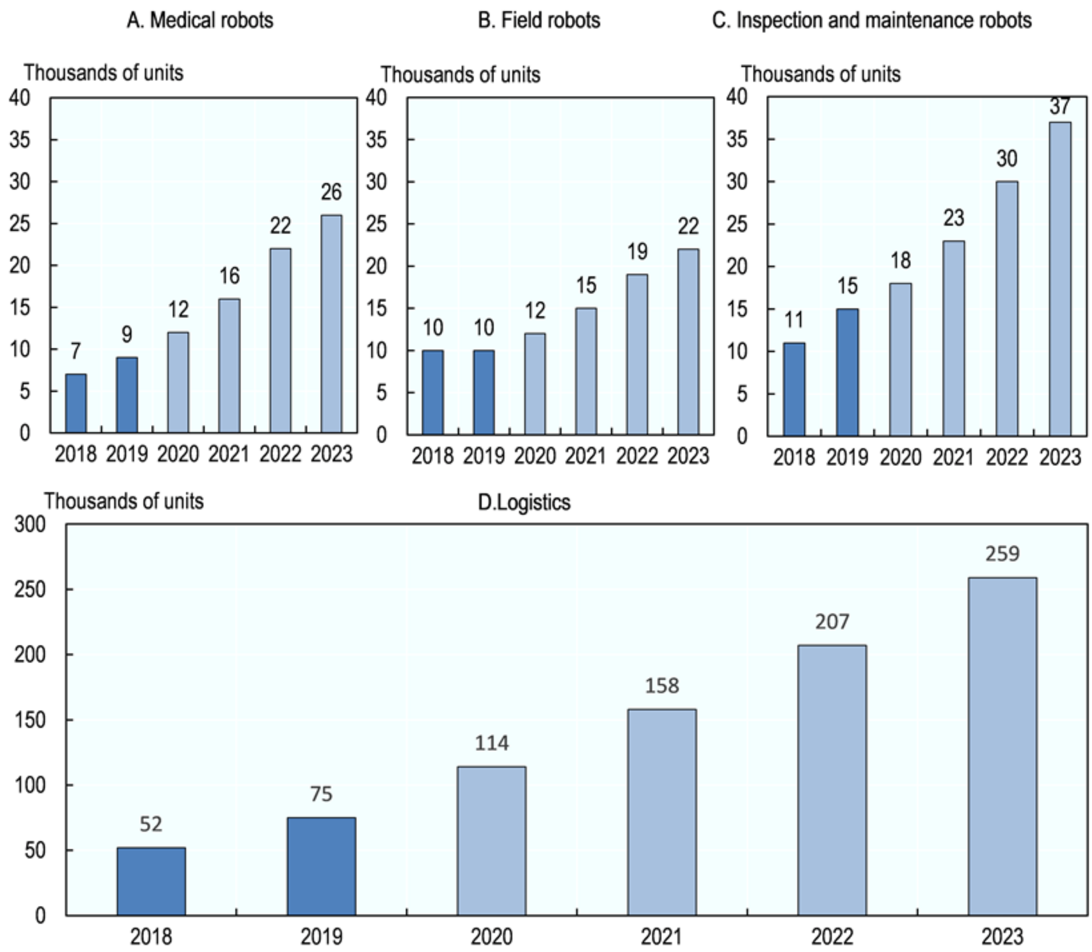
Robots in services

Around 172 000 professional service robots were sold in 2019. This numbers is forecast to rise to 537 000 units by 2023 (IFR, 2020). Figure 9 illustrates data on purchases of professional service robots in main applications relevant to this paper (data are omitted for robots used in defence, as well as in public environments such as hotels and restaurants). Robots have a growing range of roles in services. They have, or could soon have, roles in such fields as:

- **Disaster relief and emergency response**: Robots can fly, tunnel, swim and crawl through disaster scenes to facilitate rescue (figure 10). A robot snake is credited with saving lives in the search for victims after the September 2017 earthquake in Mexico (Hutson, 2017). In the United States, 2020 saw the first use of a firefighting robot, the RS3, which fought a blaze in Los Angeles.
- **Infrastructure maintenance and management**: Robots can help make power systems more resilient, and inspect and maintain bridges, convoluted pipelines and wastewater systems, roads and other essential infrastructure (Zhu and Başar, 2011). Several types of robot have been deployed at the Fukushima-Daiichi nuclear plant since the disaster in 2011. Working in a highly radioactive environment, one of their most important and challenging tasks is to collect debris of melted nuclear fuel from beneath the reactor. The debris will provide data that could help develop accident-tolerant nuclear fuel.[9] Robots can also climb and maintain wind turbines (Robotics-VO, 2013), and help to sort and process complex waste (Pransky, 2020).

- **Logistics**: Kiva Systems warehouse robots handle four times as many orders as un-automated warehouses. They learn, for example, to store less frequently ordered products in more remote areas (Rotman, 2013).
- **Construction**: Robots also perform some construction tasks, particularly in Japan. The Obayashi Corporation, one of Japan's largest construction companies, is currently building a major dam in south-east Japan with extensive use of robots (Sakurai, 2020).
- **Exploration for natural resources**: EU-funded research has helped develop an autonomous underwater robot that maps abandoned and flooded mines, searching for unused mineral deposits (Coxworth, 2019).

Figure 9. Purchases and main applications of service robots for professional use, 2018-2019, and projected to 2023



Note: Field robots are non-factory robots designed for unstructured and often dynamic environments on land, sea and air, for instance in mining, agriculture and underwater exploration.
Source: IFR (2020), *World Robotics Report 2020.*

Figure 10. A robot snake developed at Carnegie Mellon University has successfully helped in search and rescue

With permission: Carnegie Mellon University.

However, much service-sector work involves non-routine physical and cognitive tasks, and requires attributes such as physical versatility and interpersonal communication skills. Such requirements have slowed the spread of service-sector robots to date.

Robots in education

Robots are beginning to find useful applications in education, aided by advances in the science of learning. Research at the University of Twente showed that when primary school children learn alongside a robot displaying facial expressions and social behaviour, they can better explain to an adult what they are studying, and make more links between relevant pieces of information. Children gave the same answers when responding to questions irrespective of whether the lesson was taught on a computer tablet or using a social robot, but those who learned with a robot understood the subject better (Van der Velde, 2020).[10] Social robots have achieved outcomes similar to human tutors on restricted tasks (Belpaeme, *et al.*, 2018). SoftBank, the Japanese conglomerate, reports that the fastest growing market for its widely sold Pepper humanoid robot is in education, in part to teach coding.

Among other topics, research is examining how a robot's appearance and behaviour affect student learning. For example, Finkelstein *et al*., (2013) show that in low-resource schools a virtual teacher (a digital avatar) that has the same accent as students produces more learning gains than a virtual teacher with another accent. Gender-ambiguous robots might also foster more diverse participation in STEM education, a possibility being studied by SoftBank.

Robots in space and the oceans

Exploration of the remote and hostile environments of space and the oceans has spurred innovation in robotics. Marine technologists have achieved much progress in developing unmanned surface vessels (USVs) and autonomous underwater vehicles (AUV's). Currently available systems can reach previously inaccessible marine environments (e.g. below the polar icecaps), reduce risk as humans interact with the ocean, and function as cost-effective ocean and marine observation platforms. Such robots can acquire data for marine and coastal science and assist in data acquisition, operations and maintenance for offshore industries. They are able to inspect the physical integrity of undersea pipelines and communication cables, among other functions, and can operate in networked groups to maximise coverage. Such groups can comprise underwater and surface vehicles at the same time.

Marine roboticists have also been inspired by marine fauna. An example is a robot crab, designed by Italian researchers, that clears the seabed of plastics (Ridden, 2019). Researchers in Norway have developed a subsea snake robot for inspection, maintenance and repair of offshore infrastructure.

Space agencies have developed robots since the beginning of the space age (OECD, 2019a). Planetary and asteroid exploration has been facilitated by autonomous vehicles, such as NASA's family of Mars rovers (Curiosity, Spirit and Opportunity). These have helped to map the Mars surface in detail, and to test its soil for water. In 2018, the Japanese Hayabusa 2 spacecraft (Peregrine falcon) landed a mobile rover on the surface of an asteroid, retrieving a surface sample that was brought to Earth in December 2020. NASA has also developed robots to capture and remove space debris and service spacecraft.

Several space agencies encourage innovation in robotics through different schemes, such as the NASA's Space Robotics Challenge, which ends in 2021. To win the USD 1 million prize, participants must develop a team of autonomous robots to successfully detect and excavate resources on the moon, such as water and methane.

Technologies used in robots developed to pursue space-related objectives have also been transferred to other sectors. Recently, the German Aerospace Center's Institute for Robotics and Mechatronics licensed technologies used on the International Space Station to a medical equipment company to develop robotic arms for surgery.

A problem for robots in space is the delay in communicating and receiving signals across great distance. Achieving greater autonomy is therefore crucial. An approach being studied is for an operator to scan and move through the robot's environment using virtual reality and then send multiple commands in batches.

Robots, healthcare and COVID-19

In 2018, sales of medical robots reached USD 2.8 billion, making this the most valuable segment of the market for services robots. 5 100 units were sold in 2018, a number forecast to rise to 19 700 units by 2022 (IFR, 2019). Robots have many roles in healthcare. These range from aiding laboratory research and testing, to surgery, physical rehabilitation, improving medical diagnostics and treatments, reducing injury among nurses, delivering medicines, transporting waste, supporting elder care, and providing behavioural therapy and cognitive support. Some applications, such as waste delivery, are well established. Others are more recent, such as uses in behavioural therapy and intelligent laboratory research.

Most robots used in healthcare today serve relatively simple functions (with the exception of surgical robots, exoskeletons, advanced prosthetics, and systems to aid rehabilitation). Advances in robotics will spur wider diffusion and more sophisticated applications. Progress could increase the resilience of health systems in the face of new diseases and help cope with longer-term pressures. For example, comprehensive use of robots in elderly care is likely to become essential as the global population ages. Moreover, by improving working conditions in many occupations outside of healthcare, robots can alleviate expensive medical problems, benefitting firms and society more broadly.

COVID-19 has focused attention on how robots might assist the response to the crisis and reduce infection risks and stress among frontline health workers. As the crisis began, leading roboticists wrote an editorial in *Science Robotics*, a journal of the American Association for the Advancement of Science, highlighting the potential of robots to combat the pandemic and infectious diseases more generally. The authors called on governments to enhance preparedness by funding multidisciplinary basic and applied science, bringing together engineers, infectious disease professionals and scientists to work in partnerships between government agencies and industry (Yang, *et al*., 2020).

This section shows how robots have aided – or begun to aid - the crisis response, for instance by increasing the rate of sample testing, speeding disinfection in some laboratories and hospitals, safely dispensing advice to the public at clinics and hospitals, and – in a recent development – automating nasal swabs. At least 66 different social robots have been adopted worldwide in response to the coronavirus outbreak (Aymerich-Franch and Ferrer, 2020). However, for reasons described in box 7, their overall contribution has been small. Many of the technologies described in section 3 must improve if robots are to significantly reduce the effects of future pandemics.

If more lethal or contagious pathogens than SARS-CoV-2 arise in future – which informed opinion suggests is only a matter of time (Ipbes, 2020) - robots could confer greater resilience on society as whole, above and beyond their specific impacts on healthcare: robots might operate essential services such as waste treatment, power generation and public transport, for example, which in the COVID-19 crisis have only functioned thanks to risk-exposed workers.

The remainder of this section considers the main uses of robots in healthcare and some of the most recent advances. Also discussed are technical and economic barriers to more extensive use, and the priorities for research to achieve the needed progress. Emphasis is placed on robot uses that counter infectious diseases.

Box 7. "In my opinion"
When can we expect robotics to make healthcare systems more resilient?
Gregory Ameyugo, Head of Ambient Intelligence and Interactive Systems, the *Atomic and Alternative Energies Commission* (CEA), France

The initial peak of the COVID-19 crisis provides lessons for the future of robotics in healthcare. The biggest questions are whether they can become an instrument for greater resilience, and when.

Industry, research and academia have all made great efforts to help address the worst of the pandemic. Open collaboration models have helped to share ideas, data and information, and design and build solutions that range from masks and spare parts to complex devices and robots for assistance, disinfection, etc.. However, because of three main hurdles, only a small percentage of the initiatives have made it to the bedside of COVID patients:

1) Technological hurdles: the current capabilities of robotic systems are inadequate for the complex reality of a crisis.
2) Domain-specific hurdles: the regulatory environment in healthcare is geared towards safety, and makes it difficult to innovate.
3) Ecosystem hurdles: healthcare innovation ecosystems able to pull innovations through are few.

Technological hurdles. Although healthcare robotics is a growing market, current applications address well-defined tasks such as patient assistance, intralogistics in a well-defined physical and IT environment, and surgical tasks controlled by a human surgeon. By definition, a crisis stretches the capacities of the healthcare system, creating a need to treat more patients in less time. Without detracting from the enormous physical, psychological and emotional efforts made by healthcare workers, humans can adapt with relative ease to the following:

- **New physical environments**, such as mobile hospitals, special COVID annexes, and even temporary clinics placed in a tent on a parking lot. These environments are more chaotic and crowded than usual, making navigation more difficult.
- **Strained / insufficient IT infrastructure** where switching to alternative means of transferring patient information (e.g. tablets or paper) are necessary. This includes issues of digital connectivity, data storage, and platform compatibility.
- **Non-standard equipment**, **treatments** and **protocols**. In the case of a previously unknown pathogen, these can evolve every week as new information becomes available.

Adapting to such environments is difficult for robots. In particular, deficits in the following capabilities limit their application:

- Mobility in unknown and/or crowded spaces.
- Easy task programming.
- Easy physical and software adaptation to new tools, actions, etc.
- Autonomy, constraints on which stem from a very limited ability to understand and adapt to a changing context.

For these reasons, cost-benefit analyses of whether to deploy robotics solutions during the crisis have been mostly negative. For example, disinfection robots have had little impact because of their limited ability to navigate in uncertain environments, deal with obstacles, detect and reach shadow areas, etc.

Looking beyond the limitations inherent to robot use in particular healthcare tasks, a common theme emerges: the main constraint today is in the capacity of robots to work in a human environment. That environment is uncertain, changing, and involves a significant amount of information being exchanged orally or by other non-standardised means.

Domain-specific hurdles have prevented many industrial, academic and other projects from bearing fruit. Among these hurdles, healthcare is one of the most regulated activities, and for good reason: lives are at stake. Healthcare regulations cover many of the robot uses. The moment they touch the patient, robots become medical devices and are subject to stringent requirements that cover everything from the materials the robot is made of, to the number of disinfection cycles they undergo, how the information they gather is presented, and even the specific units to be used for the measurements they take. The process to bring such devices to the market is lengthy, and for Class II devices and beyond (those used to perform actions on the patient) animal testing might be required even before running a human pilot.

Every change to an existing device triggers an approval process. While the health industry is used to dealing with this framework, it introduces a level of inertia incompatible with a fast crisis response.

The specificity of healthcare becomes critical when we consider the use of AI, and in particular machine learning. Healthcare is heavily regulated and focused on safety, like the aerospace and nuclear industry, but is much more "collaborative" than these sectors, in the sense that human-robot collaboration is a constant. It is therefore not surprising that the most successful robotic initiatives during the crisis have been those for laboratory robotics, e.g. to process PCR tests faster. The full potential of robotics for healthcare crisis response will not be realised without an evolution in the regulatory framework. Countries like France and Singapore are aware of this and have launched sandbox initiatives to help understand how to respond.

Ecosystem hurdles have been the final limiting factor for robotics initiatives in the COVID crisis. Bringing a robot into hospitals requires access to doctors, regulatory bodies, medical researchers, industrial companies and other institutions. An ideal ecosystem would bring these key players together. Such ecosystems exist in different places - for example, Clinatec in Grenoble in France, and Aachen in Germany - and some of the more successful initiatives during the crisis stem from ecosystems of this sort.

In the case of CEA, the success of the CLEAR project (for ventilator monitoring) stemmed from the PASREL project (***PA***ris, ***S***aclay, ***RE***search and hospita***L***), a healthcare innovation hub focused on operational excellence under construction in Saclay, and already active in deploying AI in regional hospitals. PASREL brings together research, academia, and healthcare institutions, giving the CEA robotics team access to 9 hospital respiratory units, veterinary institutes and other key actors that has made it possible to move from paper to patient in as little as 4 weeks.

From the above, we can draw the following conclusions:

1) Robots cannot yet add significant resilience to the healthcare system.

2) The complex and human nature of healthcare crises places a premium on interaction technologies that allow robots to be deployed and redeployed with less effort, such as intuitive programming and natural language processing. Indeed, AI has the potential to greatly enhance the role of robotics in healthcare.

3) The regulatory environment in healthcare calls for a wider deployment of sandboxes, and an acceleration of efforts to allow deployment of AI-enabled robotics.

4) The development of healthcare innovation hubs that bring together healthcare providers, research and academia, industry and regulatory actors has been shown to be successful.

Robots in the laboratory

Laboratory automation is essential in many fields of science. Robots have helped automate routine laboratory processes for some years, mainly in tasks in chemical and biological research such as pipetting. Today, AI-enabled laboratory robots can go beyond mere mechanical tasks and execute closed-loop cycles of testing, hypothesis generation and renewed testing (figure 11). They can generate and test hundreds of hypotheses in parallel, and screen and test thousands of pharmaceutical compounds per day. Laboratory robots can also record experimental procedures and associated metadata automatically, which aids accurate reproduction of research. In 2009, Adam, a laboratory robot developed by researchers at the universities of Aberystwyth and Cambridge, became the first such system to make an independent scientific discovery (concerning the genomics of baker's yeast). However, laboratory robots are costly and difficult to use. The high cost reflects the small number of robots sold and the market's immaturity (King and Roberts, 2018). As well as contributing to research, laboratory robots have helped accelerate testing for COVID-19.

For example, the VIB-VUB Centre for Structural Biology in Brussels has used its KingFisher robot to perform an additional 1 000 tests per day (euRobotics, 2020).

Figure 11. An autonomous laboratory robot at the University of Liverpool chooses its own experiments

This robot chemist developed at the University of Liverpool moves about the laboratory guided by Lidar and touch sensors. An algorithm lets the robot explore almost 100 million possible experiments, choosing which to do next based on previous test results. The robot can operate for days, stopping only to charge its batteries.

With permission: University of Liverpool.

However, adding AI to robots is not enough to improve the entire process of laboratory testing, especially in a crisis. Also needed is greater flexibility in handling, combining vision, gripping tools and grip sensing. At the height of the pandemic, laboratories faced shortages of test-kits, and medical practitioners received patient samples in many types of container, with no standardised shapes and sizes. To handle, open and extract the samples for testing required human-level dexterity. Most automated processes could not deal with this variance. Some robot systems could have done this, but were not used owing to the high costs of installation, programming and ancillary sensing equipment.

Robots in patient screening and initial care

During the first COVID-19 peak in the second quarter of 2020, patients arriving at Antwerp's University Hospital were greeted by a robot that checked whether they were wearing masks, ensured the masks were positioned properly, screened patients for signs of fever and admitted those who could safely attend an appointment. The system, which speaks 35 languages, reduces crowding among waiting patients and lowers infection risk for staff (Parrock, 2020).

Nasal and throat swabs are the current standard for initial diagnostic testing for COVID-19. This requires qualified personnel, whose time is scarce when demand is high. In response, researchers have developed a fully automated robot that performs the delicate task of taking swabs. Using AI and cameras to apply swabs precisely, the robot can improve sample quality and reduce infection exposure for nurses (Filks and Skydsgaard, 2020).

Research goals for robots in patient screening and initial care

Researchers aim to improve how robots can interact with patients remotely, such as through high-resolution cameras to measure pulse rate from the skin, and sensors to measure oxygen saturation from a distance. Since drawing blood carries a risk of exposure for medical staff, engineers are examining ultrasound imaging of veins for robotic venepuncture (Yang *et al.*, 2018). More challenging still would be robotic emergency medical technicians (EMTs). EMTs perform complex cognitive and physical tasks, such as rapid assessment of a patient's condition and inserting breathing tubes (inserting breathing tubes is also one of the riskiest procedures when treating a suspected COVID-19 patient, as the chances of being splattered by upper respiratory bodily fluids are high). If AI-enabled robots could assist EMTs, more attention could shift to the most urgent procedures. Creating robotic EMTs would require advances in many of the technologies discussed in section 3, such as understanding spoken natural language, recognising gestures and anatomical structures under chaotic conditions, and improving actuators, such as hand-like grippers (Yang *et al.*, 2018). The preceding section on laboratory robots also described the difficulties robots have in handling patient test samples in non-standard containers. Better manipulation, to help address this problem, is a generic challenge in robotics.

Robot surgeons

The first documented case of a robot assisting surgeons occurred in 1985, when a robot arm helped to biopsy neurological tissue. Surgical robots are now categorised under three broad types: active systems that perform pre-programmed tasks under human supervision (such as placement of needles in some forms of radiology); semi-active systems where a surgeon complements an active system; and systems under a surgeon's sole control, which precisely reproduce the surgeon's hand movements (Lane, 2018). Most experts consider fully autonomous robot surgeons a distant prospect.

Several thousand prostate operations using minimally invasive robots are performed every year in the United States. These robotic procedures reportedly lead to shorter admission periods, fewer infections and faster recovery (Computing Community Consortium/Computing Research Association, 2009). The first successful treatment of a brain aneurysm by a robot was announced in 2020 (American Heart Association, 2020). Robotic kidney transplantation is increasing around the world. 2001 saw the first surgery in which the patient and the surgeon were in different countries. Some systems afford the surgeon a physical sensation of what the robot touches. Non-invasive abdominal surgery, cardiac surgery, neurosurgery, orthopaedic surgery and many others are now part of the market for medical robotics.

To complement surgeons, robots can have more limbs, digits and freedom of movement than a human (figure 12). They do not tire or get distracted, they can operate consistently and with sub-millimetre precision, and surgeons can quickly learn their use (Weisz, *et al.* 2014). A new system developed for super-microsurgery, the Microsure Musa, scales down the surgeon's movements and compensates for hand tremor (figure 13). Thus, robots may lower the frequency of preventable surgical errors.

Figure 12. A Da Vinci surgical robot, designed for minimally-invasive surgeries, uses multiple arms with many degrees of freedom

Source: Intuitive surgical.

Figure 13. Designed for super-microsurgery the Musa robot can scale down a surgeon's movements and filter hand-tremor

With permission: Microsure.

Research goals for surgical robots

A key challenge in surgical robotics is achieving greater intelligence. Compared to the largely standardised work of industrial robotics, surgical robotics has to deal with much greater variation and uncertainty, for instance in patients' bodies and surgical needs, as well as in the course of any individual surgery. Robots need more intelligence to be more useful in such environments. Beyond traditional but limited clinical decision-support tools – such as decision trees - engineers are attempting to integrate the most synergistic features of human and machine intelligence, with humans and machines working together to enhance *in situ* surgical decision-making (Loftus *et al.*, 2019). Among many other topics, research is examining how robot surgeons might learn from human surgeons, share control of some steps in an operation, observe a surgeon's gaze, and even record procedures and provide feedback.

Also helpful would be improvements in assistive robot technologies, other than robot surgeons, that increase surgical effectiveness and safety. An example is robot technology to map the body's interior and help guide surgical tools to the right location. For instance, Tully *et al.,* (2011) demonstrate how a highly articulated (snake-like) miniature robot could enter the heart and help render a 3D image while compensating for the heart's movement as it beats.

Another goal is to better measure the clinical efficacy and secondary outcomes of robotic surgery. Gains in accuracy or efficiency in some part of a surgical procedure might be offset by other features of a robotic system. For example, the need to reconfigure a robot's tools during surgery could lengthen the time spent by a patient under anaesthesia. Cost-benefit analyses of the use of surgical robots might also miss variables relevant to a crisis, such as the benefit from treating patients more rapidly when hospital beds are scarce.

Box 8. "In my opinion"

Robots in surgery and other fields of healthcare – some future research priorities

Kaspar Althoefer – Professor of Robotics Engineering, Queen Mary University of London

Recent developments in soft robotics have had a noticeable impact in medicine, with new research focusing on creating soft robotic devices for surgery, rehabilitation, care of the elderly and treatment of mental disorders. Arguably, the first research initiative exploring soft robot arms for minimally invasive surgery was the EU-funded project STIFF-FLOP, which ran from 2012 to 2015. STIFF-FLOP sought inspiration from nature, in particular the octopus, to create, for the first time, soft, tentacle-like robotised instruments that could penetrate a patient's abdomen safely and with dexterity to aid surgeons in diagnostic and therapeutic procedures. Morphological computation hypothesises that the body itself can accomplish aspects of motion, effectively acting as an intelligent but mechanics-based processing unit. At the interface of AI-based reasoning and morphological computation, STIFF-FLOP successfully showed that a system that fuses hardware intelligence and cognitive software has the potential to conduct complex procedures in the harsh and highly unstable environment of the human abdomen, keeping the surgeon in the loop and, above all, satisfying the most stringent safety standards. Importantly, by transferring some of the processing power to the mechanical elements of a robot, the requirements for computational resources can be considerably reduced. STIFF-FLOP broke new ground in minimally invasive surgery and initiated further research in the new area of soft robotics for medicine.

With advances in algorithms, especially in the fields of data science, AI, interaction modelling and control, coupled with increasing computer power and progress in materials science, new devices are emerging capable of performing tasks that were previously impossible. Whilst there are undeniable advantages in using AI-based techniques, they have a major shortcoming, namely that the behaviour of a learnt system, such as a neural network or deep neural network, cannot be understood or predicted. Hence, there are significant safety implications when using such data-centric approaches within the control architecture of a robotic device. For example, a medical robotic system that is in physical contact with a human must keep the occurring human-robot interaction forces within safe limits. Research will need to focus on developing explainable AI algorithms with clear operational boundaries. Research will also need to advance software in parallel with advancing hardware.

Soft robotic concepts are important building blocks in the development of holistic robotic systems, allowing the realisation of motion patterns that adapt to the environment. In other words, elements of the overall robotic system's intelligence are integrated in the robot's hardware, reducing the burden on the computing system.

Biology clearly shows that the body's structure can handle important aspects of physical interaction with the environment. For example, the limbs of an octopus can softly adapt to every undulation of the environment, but can also apply high forces when required. However, most aspects of the actions taken are not due to commands executed in the octopus's brain, but are instead inherent to the structural make-up of the arms. Realising novel robot systems that amalgamate new hardware solutions with appropriately correlated software will be key in creating medical devices that can operate on humans in a safe way and with increased autonomy.

Robotic exoskeletons in healthcare

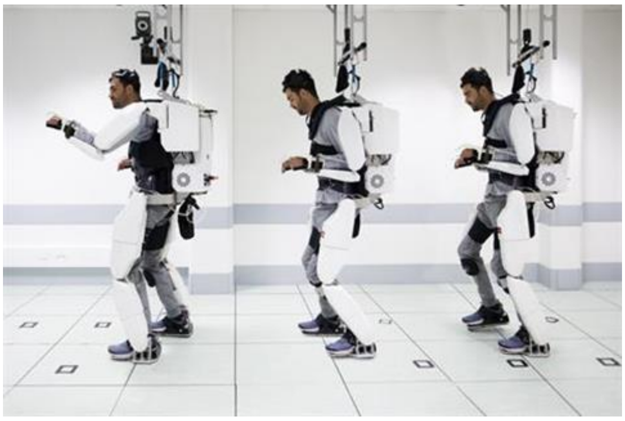
An exoskeleton is a hard or soft structure that fits around one or more body parts and affords physical support. Active systems that amplify some aspect(s) of the wearer's abilities now complement passive exoskeletons, which only give static support.

One use of exoskeletons is in physical rehabilitation. Exoskeletons can interpret the kinetic properties of a person's movements in real time, helping patients such as stroke victims perform therapeutic movements precisely. Some exoskeletons give data-driven performance and motivational feedback, suggesting adjustments to the difficulty of therapeutic tasks. Exoskeletons can also deliver lengthy personalised therapy without tiring. Rehabilitation systems need not be limited to formal programmes of therapy: they can also assist general mobility, for instance for persons with spinal cord injuries.

A notable recent breakthrough comes from the French *Atomic and Alternative Energies Commission*, which developed a brain-controlled exoskeleton that allows a subject with four paralysed limbs to walk, achieving control over arms and legs (figure 14). This success relies in part on progress in neurobotics, the study of the brain in conjunction with technology.

Assistive exoskeletons are beginning to help protect healthcare workers from injury. Nurses in particular are prone to injuries in moving and lifting patients. In fact, nurses face greater risk of injury than workers in factories, construction and other jobs involving physical labour (White, 2015). Wearable exoskeletons can also reduce a surgeon's fatigue during long operations.[11]

Figure 14. A brain-controlled robot exoskeleton helps a tetraplegic patient to walk



With permission: CEA.

Robots in the medical supply chain

In a growing number of Chinese towns and cities drones have been used to share information (over loudspeakers), spray disinfectant, deliver medical supplies, and even take people's temperatures (using thermal imaging). Drones routinely fly to the centre for disease control in Xinchang County, traversing China's first anti-COVID-19 "urban air transport channel" (Cozzens, 2020). Such systems can also help deliver medical supplies to remote regions. For instance, companies in the United Kingdom partnered to deliver COVID-19 tests to a remote island off the Scottish coast. Drones could also help in developing countries where road coverage may be limited and/or roads are poorly maintained. Zipline, an American company, designs, builds and operates drones to transport blood, and has made tens of thousands of deliveries to isolated locations in Ghana and Rwanda.

Autonomous hospital-delivery robots

Robots are freeing the time of hospital staff by transporting hazardous materials, laboratory specimens, medications and meals for persons in quarantine. Many hospital robots respond to requests placed through touch screen interfaces, performing tasks and then returning autonomously to charging points. Robots are also being designed to perform tasks in hospital kitchens and pantries.[12]

Robot disinfectors

Hospital-acquired (nosocomial) infections are a leading cause of death in OECD countries. They also impose major costs on health systems. Short-wave highly energetic ultra violet (UV) light can destroy genetic material in bacteria and viruses. Robots equipped with UV light can disinfect frequently touched areas, lower workloads and reduce risk exposure compared to manual disinfection. In response to COVID-19, *Bucharest Robots* deployed a UV robot that disinfected a hospital space spanning 7 500 m^2 in just a few hours (euRobot, 2020). Robotic disinfectors have been available for many years. However, they are not yet widely deployed, and need significantly improved capabilities before they play a major role in health systems (Box 7).

Research goals for robot disinfection

Further research could help develop micro-scale and larger robots that continuously identify and sterilise areas of high infection risk (Yang, *et al*., 2018). Robot disinfection systems require improved capabilities to navigate uncertain environments, deal with obstacles, detect and reach shadow areas, among others (Box 7).

Micro-robots for drug delivery

There are two main types of medical micro-robot, man-made and bio-hybrid. For some years experimentation has advanced on injecting subjects with metallic particles containing a therapeutic cargo and steering these to a disease site using magnetic fields from outside the body. Such systems have effectively restricted blood flow to tumours in mice. Among man-made micro-robots, systems are just emerging that sense and record information about micro-scale environments in the body and move under their own power (see Section 3). Molecular-scale robots that sense tumours to deliver drugs precisely are also under study. Progress in materials science has been important for micro-robotics. For instance, materials have been created that respond to changes in acidity and temperature, and other stimuli, by changing shape to release medication.

Bio-hybrid micro-robots integrate biological and man-made components (such as nano-tubes, nano-particles and micro-machines). The biological components complement the man-made components. Bacteria, for example, can self-propel in ways that most man-made systems cannot, leading researchers to examine if bacterial swarms can be used to push man-made drug delivery devices. Bacterial micro-robots have been the main object of research in the field of bio-hybrid systems, and have begun to be used for drug delivery.

Research goals for micro-robots for drug delivery

Research priorities for micro-robotic drug delivery include:

- Developing biodegradable and non-toxic systems;
- Standardising safety protocols;
- Developing biocompatible energy sources to power man-made micro-robots;
- Creating systems capable of intelligent targeting and high autonomy (with on-board decision-making capabilities, for instance to control fuel consumption and actions at the target site);
- Improving catheter-based robot delivery near to diseased tissue; developing better non-invasive external controls (such as magnetic manipulation), including for on-command release of drugs;
- Devising systems for monitoring and control of swarms of micro-robots; and,
- Developing therapies well suited for robotic delivery (Erkoc, *et al*., (2018), and Yang, *et al*., (2018)).

Robots supporting mental health

Research has recently begun on the possible role of robots in mental health. Autism spectrum disorder, which affects around 1 in 160 children worldwide, is one area of research (Box 9). Loneliness is a growing problem in OECD countries, and the isolation felt by many during COVID-19 lockdowns has often led to mental stress. Robot systems can diminish loneliness in some people (see the next section). A robot that speaks encouraging phrases can have a positive impact on a person's mood and game-playing performance. Interaction with the PARO therapeutic robot – which looks like a seal - has improved the mood of dementia patients and reduced feelings of isolation (Robinson, Broadbent and MacDonald, 2016).

The possibility of further robot uses in mental health is hinted at by experiments showing that a humanoid robot seated opposite to and gazing at a human subject can cause motor interference in the subject, to a point where the behaviour of the robot might subtly guide human behaviour as the two adapt to each other (Ehrlich and Cheng, 2018).

Box 9. Using robots and AI to help people with Autism Spectrum Disorder (ASD)

Speech and behaviour therapies can be of help to children with ASD, but are also costly, time-consuming, and require tailoring to the needs of each child. Researchers at the University of Southern California recently developed a machine-learning model that analyses dialogue and visual data to assess children's engagement with therapeutic activity. In testing, and despite noisy data, the model predicted children's engagement with 90% accuracy (Jain, 2020). The robot acts to re-engage the child when necessary.

To study if they could improve social skills in children with ASD, Scasselati *et al.*, (2018) took robots out of the laboratory setting, where experiments are usually brief, and into homes and longer-term interactions. The robots staid in the homes of 12 children for a month. They gathered data as the children and a caregiver played social games on a touchscreen fixed to the robot, which also gave expressive feedback. The robot adapted to the children through a reinforcement-learning algorithm and adapted the difficulty of activities to past performance. The game's purpose was to teach social skills such as taking turns, seeing the perspective of others and making eye contact. Many children also began to treat the robot as a friend. Following this experience, the children showed improvement on attention skills with adults when not in the presence of the robot, along with increased communication skills and engagement with siblings. If affordable, personalized therapeutic robotics could eventually provide children with ASD with more comprehensive care.

Children with ASD have also been able to manipulate robots as these interact with humans. This safe vicarious experience affords some children greater emotional ease in every-day circumstances. Research also shows that children learning social skills via a digital avatar became better able to use those skills in interactions with real-life peers than were children taught with state of the art pedagogy using social stories (Tartaro and Cassell, 2008). Other research is studying if machine learning could amplify emotional cues in speech, making them easier to detect for somebody with ASD (New, 2019).

Research goals for robots to support mental health

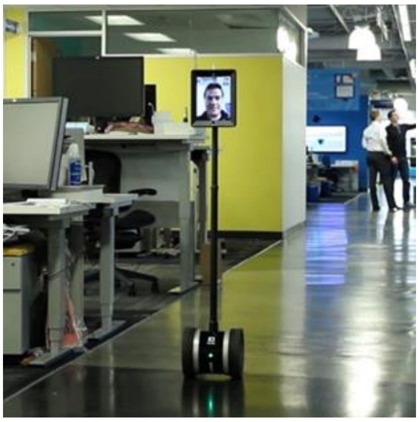
Successful development of more effective social robots would provide systems better suited for use in supporting mental health. Such robots would build and maintain multi-dimensional models of their human counterparts, understanding more of what they know, believe, feel and intend (Yang *et al*., 2018).

Robots in elder care and nursing homes

Rapid population ageing in OECD countries, and the ensuing prospect of widespread age-related physical, cognitive and socio-emotional decline, have spurred interest in how robots might help. One priority is developing robots to complement the caregiver workforce, which is slated to grow significantly. The United States alone could need 2.5 million additional long-term care workers by 2030 (Bryant, 2017). With the world's oldest population, Japan is the global leader in robotics for elder care (Box 10).

Various companies make social robots for elder care. These perform basic non-medical tasks such as reminding the elderly to take medications, while also providing cognitive stimulation and forms of companionship. A related development is systems that connect users to navigable mobile robots, allowing them to experience sights and sounds in the robot's environment. Robots that provide telepresence are proliferating thanks to their simplicity and wide range of uses, including helping convalescent or immobile patients interact with family members at home, as well as young patients attend school, and persons of any age visit museums. Luvozo's robot concierge, SAM, autonomously navigates multiple rooms to check-in with nursing home residents. However, one drawback to such robots is their high cost. Hence, some companies have responded by developing simpler and less expensive designs that interface with the user's own tablet computer (figure 15).

Figure 15. Systems like the Double 2 enable doctors, remote workers and students to interact with patients and colleagues when they can't be present in person



With permission: Double Robotics.

Research goals for robots in elder care

Elder care raises particular challenges for robot systems. For instance, older people - especially the most impaired – often interact with care-givers differently from younger adults. Robotic care for individuals requires better understanding and modelling verbal and non-verbal communication between the elderly, human carers and robot systems. Another need is lowering costs while ensuring safety (Yang *et al*., 2018). More research is required on the psychological and physical outcomes of older persons' interactions with social robots. Also helpful for policymaking would be a better understanding of the potential role of exoskeletons and other robot systems in reducing the amount of care needed by the elderly.

Box 10. Japan and robotics for elder care

Japan's population is projected to fall from 126.8 million in 2017 to just over 50 million in 2115, and 25% of Japan's workforce could be employed in elder care by 2050 (Yoshida, 2017). The global market for nursing care and assistive robots, most of which are made in Japan, was around USD 19 million in 2016. However, Japan's Ministry of Economy Trade and Industry estimates the domestic market for such robots will grow to JPY 400 billion (USD 3.8 billion) by 2035 (Foster, 2018).

The Japanese government has subsidized purchases of robots by nursing homes since 2015. Among other projects, Japan's Agency for Medical Research and Development (AMRD) is developing exoskeleton-like wearables to help nurses lift patients (for instance in and out of baths) along with robots to help the elderly use toilets unaided and enjoy greater indoor and outdoor mobility. A large majority of Japanese welcome nursing care from robots, in part to reduce burdens on health workers and family members (Japan Times, 2018). AMRD also aims to foster robot manufacturing in Japan, which could supply a growing export market as the global population ages.

Shintomi Nursing Home in Tokyo has trialled at least 20 types of care robot. Among these are communication devices with a human form, known as Telenoids, which transmit the voice and expressions of a third person over the Internet and help dementia patients to communicate. However, Telenoids are expensive, ranging in price from around JPY 400,000 (USD 3,700) to JPY 900,000 (USD 8,500) (Siripala, 2018).

A recent but so far unpublished study by researchers at Stanford University used establishment-level data to examine the impact of robot adoption on staffing in nursing homes. Facilities that adopted robots were larger, had more functionally-impaired residents, more care workers, used many other assistive technologies, had better management practices and were located in prefectures with higher planned robot subsidies per nursing home. Adopting robots had little impact on overall staffing or wages, but did lead to additional non-regular nurse hours and higher turnover of regular care workers.[13]

5. Robots and public policy

This section examines the logic, design and impact of public policies for robotics and the wider use of robots in firms and public services. It also considers options for governments to influence the direction of future developments in order to maximise the social benefits of robotics (see also OECD (2021a)).

An overarching observation, relevant to all considerations of policy, is that greater knowledge of cyber-physical systems in government will help to maximize the potential of robots for social and economic good (CCC/CRA, 2016). Some of this knowledge is domain specific: so different parts of government - ministries of health, agriculture and industry, for example - should possess up-to-date understanding of how robotics is developing in their specialised areas of competence and responsibility.

Public R&D for robotics

Based on Yang *et al*, (2018), CCC/CRA (2016) and interviews with leading roboticists, Annex 1 summarizes the "grand challenges" of robotics research (research goals for medical robots were described earlier). These challenges, possibly complemented by suggestions from other experts, could constitute targets for public R&D support. The research priorities described in Annex 1 are grouped under the following headings:

- **New materials and methods of fabrication**, for new multifunctional, power-efficient autonomous robots.
- **Sensors and perception**, for better, smaller sensors that capture information on a wide range of conditions - pressure, motion, torque, heat, etc. - with better processing of sensor data.
- **Power and energy**, for robots that can operate independently over long periods of time.
- **Robot swarms**, for simple, cheap robots that function as teams and match the performance of larger, task-specific robots.
- **Navigation and exploration in extreme and unmapped environments**, for robots to traverse difficult and unfamiliar environments, adapting and learning in real-time.
- **Artificial intelligence and formal methods**, for gains in performance across most areas of robotics.
- **Brain-computer interfaces**, for seamless control of peripheral neuro-prostheses, functional electrically stimulated devices and exoskeletons.

- **Social robots**, for robots to integrate with human social and moral norms and dynamics.
- **Ethics and security**, for responsible innovation in robotics.

Given the broad uses of robots, many public agencies and parts of government can play a role in the development of robotics, funding a wide variety of goals in robotics.

Moonshots for robotics in society

Grants, innovation-oriented public procurement and innovation prizes all have a role to play in advancing robotics and aligning progress with societal needs. Public- and private-sector challenge prizes have been prominent in the recent development of robotics. In the United States, DARPA, the Office of Naval Research and NASA have all run challenge prizes in robotics. A multi-year DARPA Grand Challenge has been central to progress in autonomous vehicle technologies. NASA's 2017 Space Robotics Challenge yielded software for robots to perform tasks in space, such as repairing air leaks. In the private sector, Amazon began a robot bin-picking challenge in early 2017, the same year that Volkswagen began its Deep Learning and Robotics Challenge.

From a policy perspective, challenge prizes are attractive because of the relatively small public investments involved: the NASA Space Robotics Challenge awarded the winning team a total of USD 300 000. Summed across all competitors, the research and development effort elicited might dwarf such prize money. Competitions can also help identify talented individuals and teams, and draw attention to ideas that deserve a second chance. Leading technology companies also hired many teams that participated in DARPA challenges for off-road and urban self-driving vehicles. Furthermore, prizes are well suited to a field like robotics that combines a large number of technologies, many of which are changing quickly. These features offer the potential to innovate using many untried technology combinations and applications. Prizes provide an open-ended incentive to generate and gather ideas from across this broad landscape of possibilities.

Careful design can raise the cost-effectiveness of challenge prizes. A recent finding is that a winner-takes-all compensation scheme (for individuals or teams) generates significantly more innovation than a scheme that offers the same total compensation shared across multiple winning innovations (Zivin and Lyons, 2020). Liquidity constraints can also discourage some firms from participating in challenge prizes (Newell and Wilson, 2005). Therefore, including an option to provide a matching grant, whereby the scheme matches some contribution from a firm, might help public funders to elicit a wider range of proposed solutions.

Establishing a portfolio of challenge prizes in robotics

A portfolio of challenge prizes in robotics could address many social goals, from helping older adults to live longer and with more autonomy in their own homes, to achieving critical safety-enhancing tasks that cannot yet be performed by robots, to combating infectious diseases and supporting healthcare systems more broadly.

Comprehensive consultation with health workers and other stakeholders could help identify and prioritise the goals of challenge prizes. Indeed, health workers might be invited to vote on which challenges should be set, just as members of the general public were recently invited to vote on the choice of a GBP 10 million challenge prize offered by the United Kingdom's National Endowment for Science, Technology and the Arts. If organised around research priorities such as those described in Annex 1, challenge prizes could also be used to add to the foundation of basic knowledge on which robotics will progress.

Challenge prizes might also be organised to build frameworks for open-access creation, collection and curation of data-corpuses, testing regimes and reference environments for the current plethora of robot systems, subsystems, components and devices (CCC/CRA, 2016).

The importance of research for benchmarking robot performance

Box 5 described new OECD work to compare human and robot cognitive and physical abilities. An overarching research challenge is to develop methods to quantify robot performance. Torricelli *et al.*, (2019) note that rigorous quantitative benchmarking will help to develop standards that accelerate the introduction of safe new robots. They show how this could be done for human-like robotic motion.

Cross-disciplinary research in robotics

Addressing research challenges in robotics requires cross-disciplinary collaborations, for instance among physicists, mathematicians, materials scientists, engineers, cognitive scientists and biologists. Policy needs to ensure that robotics is not hindered by obstacles to cross-disciplinary research, such as hiring and promotion policies, and funding systems that favour traditional disciplines. For example, roboticists who work at the interface between disciplines need to know that opportunities for tenure are not jeopardised by doing so.

Box 11 describes the Bristol Robotics Laboratory, the leading robotics institution in the United Kingdom, which has cross-disciplinary research at its core.

Public-private partnerships for robotics research

The complexity of some research challenges may exceed the research capacities of even the largest institutions, necessitating a spectrum of public-private research partnerships. In terms of resources and focus, such partnerships can help create synergies between basic and applied research. The Advanced Robotics for Manufacturing Institute (ARM) in the United States is one example of a partnership model. ARM aims to create and deploy robotics technology by integrating industry practices and institutional knowledge across many disciplines, from materials science to human and machine behaviour modelling. Another example is euRobotics, the private-sector pillar of the Partnership for Robotics in Europe (SPARC).[14] euRobotics comprises more than 250 organisations active in robotics, across research and industry. Among other objectives it develops strategic roadmaps for robotics research and innovation. SPARC is the largest civilian-funded robotics innovation programme in the world, with EUR 700 million in funding from the European Commission over 2014-20 and triple that amount from European industry.

Lechevalier, Ikeda and Nishimura (2018) analysed 25 years of public-private robot R&D partnerships in Japan, from 1993 to 2008, and found that these projects created valuable results, and also caused participating firms to be more efficient in their future independent research. Firms increased their robot technology R&D productivity on independent projects by an average of 13 percent in the years after participation in cooperative government R&D. This effect is significantly larger than purely private cooperative R&D, and also increased significantly after a reorganization of Japan's R&D agencies.

The eclectic nature of robotic technologies and their underpinning sciences means that for many countries, especially those with a small robotics sector, international cooperation in research programmes will also be valuable.

Research test-beds

Testbeds have facilitated research and innovation, lowered technological risk, and helped to speed adoption of new technologies in fields such as autonomous driving and advanced manufacturing. Some robot test-beds specialise in a particular industry, such as robotic vehicles. Test-beds will ideally be equipped with a variety of robot systems so that researchers and inventors can test how their systems' algorithms generalise, while allowing teams with theoretical results, but without equipment, to test their findings in a real-world environment (CCC/CRA, 2019).

Targeted support for technology transfer

Policy might also direct the trajectory of robotics development by providing targeted support for technology commercialisation. Many institutional settings affect knowledge transfer and commercialisation, from licensing and patenting arrangements, to the *modus operandi* of a variety of intermediary organisations such as technology transfer offices (TTOs); alliances among multiple TTOs: Internet-based platforms that complement traditional TTOs; business incubators; science parks; agencies in chambers of commerce; proof-of-concept centres (which aim to close funding gaps if business angels and venture capital companies focus on later-stage investments); seed funding programmes; tax policies affecting venture capital and business angels, and support for student entrepreneurship. Policy should optimise this eco-system regardless of the type of technology. Where social priorities are urgent, however, such as during a pandemic, accelerating technology transfer in relevant fields could help. For example, a mobile disinfection robot won the euRobotics Technology Transfer Award 2020. And under the EU's Horizon 2020 programme, a €4 million Technology Transfer Experiment for COVID-19 proposals was organised under the DIH-HERO project (euRobotics, 2020).

Box 11. The Bristol Robotics Laboratory

Bristol Robotics Laboratory (BRL) is the most comprehensive academic centre for multi-disciplinary robotics research in the United Kingdom, bringing together research, teaching and enterprise.

BRL's overarching mission is to understand the science, engineering and social role of robotics. In particular, BRL works on key challenges surrounding adaptive robotics, including developing robots that work with people, in unstructured and uncertain environments, in flexible roles. Specific research fields include artificial intelligence, smart automation, human-robot interaction, bio-energy systems, tactile sensors and haptic feedback, aerial robotics, connected autonomous vehicles, swarm robotics, assistive technologies, medical and rehabilitation robotics, robotics for nuclear environments, non-conventional computation, soft robotics and robot ethics.

In addition to research, BRL offers doctoral programmes, as well as taught courses at undergraduate and postgraduate levels. BRL runs a hardware incubator providing physical space and facilities for high-tech start-ups. BRL also operates a "Robotics Innovation Facility" that supports businesses to develop and deploy robotic technologies, including by providing mentoring, technical assistance, and access to industry specialists and investors.

On-site facilities include 37 research bays equipped with numerous robots; a laboratory for microbial fuel cell technologies; an assisted living studio for testing home robots; a driverless car workshop and test simulation suite; a robotics for nuclear environments suite; chemical and polymer laboratories; temperature controlled wet laboratories; a rapid prototyping/3D printing workshop; a hazard area for laser and x-ray testing; workshops for mechanics and technicians; and a 16 000 litre pool for testing underwater robots.

BRL's innovation pipeline feeds directly into the West of England University Enterprise Zone (UEZ), which adjoins the robotics laboratory. UEZ connects entrepreneurs and technology innovators with scientists, researchers and graduates to accelerate collaboration and innovation. The UEZ also houses the "Health Technology Hub" and the "Robotics Innovation Facility" (RIF). RIF addresses the technology transfer gap between academic research and industrial take-up, and provides 'near to market' research facilities for SMEs to develop ideas and implement new robot-based solutions. BRL also runs the West of England Robotics Network, which supports commercialisation of products and services (more than 80 companies are part of BRL's enterprise eco-system). All of the above networks and programmes give researchers first-hand insight into commercialisation processes.

Source: www.brl.ac.uk

Identifying gaps in the institutional landscape for robotics

For countries that have a significant base of - or potential for - robotics research, policymakers should examine if all the important stages of research and commercialisation have proper institutional support. Institutional gaps can hinder progress. For instance, with respect to new robots for healthcare: institutions that fund health research may lack knowledge of robotics; funders of science research can lack expertise in the day-to-day realities of medical practice; and, new robot technology might be too commercially immature to interest venture capitalists. An example from healthcare robotics in the United States illustrates the point:

> "Funding is specifically needed in the areas of incubating and producing complete systems and evaluating those on patient populations in trials that are a year long or longer. Currently no funding agency exists for such incubation: the research is too technological for NIH [the National Institutes of Health], too medical for NSF [the National Science Foundation], and too far removed from an immediate market to be funded by business or venture capital. As a result, there is a lack of critical mass of new, tested and deployed technological innovations, products and businesses to create an industry." CCC/CRA (2016), page 46.

Good ideas might end up stranded in an institutional landscape that fails to find them. A national review of the relevant institutions and their boundaries could suggest solutions if gaps are found.

Successful robotics eco-systems are nurtured by the economic and institutional conditions in specific locations (Box 7). Co-located doctors, regulatory bodies, medical researchers, industrial companies, and other institutions exist in such places as Grenoble, France, and Aachen, Germany. Synergies arise in such locations, where expertise, knowledge, hardware and finance exist in close proximity and information spill-overs are abundant. Trying to create such clusters *ab initio* is not straightforward: clusters emerge because of complex socio-economic conditions that are hard to replicate, and policies that aim to do so have often failed. In most sectors, from pharmaceuticals to aerospace, industrial clusters have arisen organically, often over many decades, or longer, without the guidance of government. However, policymakers can strengthen such clusters when making decisions on the location and funding of infrastructure, complementary institutions (such as metrology bodies and training institutes), and public research institutions (R&D

laboratories are up to six times more likely to develop a patent through collaboration if they are near to other laboratories than if they are located alone (Buzard *et al.*, 2017)).

Diffusion

The use of industrial robots varies greatly by region, country and size of firm. Adoption of industrial and medical robots is also slow, given the scale and importance of the challenges they could help to address. This section considers the diffusion of robot use in industry and healthcare, its determinants, and policies to facilitate diffusion.

Industrial robot uptake across countries and regions

Robot uptake across countries and regions is highly uneven. South Korea has the highest robot density in the world, with 710 industrial robots per 10 000 manufacturing workers in 2017, followed by Singapore, with 658. Germany, ranked third globally, had 322, the United States 200, and China 97 (IFR, 2018).

In 2019 Asia installed 245 000 industrial robots, compared with 72 000 in Europe. This gap is projected to increase rapidly, with Asia installing 420 000 robots in 2022 and Europe just 87 000 (figure 16).

Explaining differences in robot use across countries is not straightforward. A better understanding of the causes of cross-country differences could help countries to define their policy priorities. One cause of cross-country differences is the sectoral composition of industry, in particular the size of the automotive sector, the first sector to deploy robots at scale and still a main user of robot technologies (a typical automobile assembly plant might have around 1 000 robots). However, some countries with low robot use also have large automotive sectors relative to their manufacturing base (Atkinson, 2019).

Because higher wages give firms an incentive to automate, worker compensation might also affect cross-country differences in robot use. However, Atkinson (2019) shows that controlling for wages, major cross-country differences still exist in adoption, with East Asian nations occupying six of the top seven places globally. Korea, for example, has adopted 2.4 times more robots than expected, given its level of worker compensation. All EU countries – except for Slovenia and the Czech Republic - have lower-than-expected adoption rates.

Cultural attitudes may also play a role in robot adoption. Attitudes towards social robots can predict their use (Heerink *et al*., 2010). Atkinson (2019) also reports a small positive correlation between wage-adjusted adoption of industrial robots and a population's affirmative beliefs that robots will be important in the future. Robots are perceived more positively in Japan and Korea than in the United States (Lee and Šabanović, 2014).

Public attitudes to robots might be amenable to influence over time. Various strands of research suggest that entrepreneurship and innovation involve an element of imitation.[15] With this in mind, policymakers might publicise beneficial and/or novel uses of robots. Kriz *et al*. (2010) show that some people's attitudes towards robots are not based on objective knowledge (but derive from science fiction). This also suggests that dissemination of information on real-world examples of what robots are and can do has the potential for changing attitudes. Robotics might be popularised in other ways too, such as through support for exhibitions and trade fairs. Estonia, for instance, with a population of approximately 1.3 million, hosts 'Robotex International', billed as 'the biggest robotics festival on the planet'. In 2017 the event attracted an audience of 27 000 and displayed 1 346 robots. The Robotex project has run for over 18 years and has become a global robotics education network (Cowan, 2019).

National robotics strategies have also been developed in some countries that lead in robotics and robot adoption, such as Japan and Korea (Box 12).

Box 12. Examples of national robotics strategies

Led by China, Japan, Germany, Korea, and the United States, all robotics-related strategies aim to increase the use of robots in industry, with differences however in funding priorities.

Japan was the world's leading industrial robot manufacturer in 2018, accounting for 52% of the global supply. Under the "New Robot Strategy", the country increased its R&D budget for robotics to USD 351 million (JPY 36.9 billion) in 2019, with the aim of making Japan the world leader in robotics innovation. Japan also has strategic goals in the field of robots for elder care (Box 10).

Korea's "Intelligent Robot Development and Supply Promotion Act" focuses on the role of robots in advanced manufacturing. The country's 2019 "Basic Plan for Intelligent Robots" proposed that public support be targeted at promising areas of robot development and use.

The European Union's "Horizon 2020" programme supports many fields of robotics R&D, including in manufacturing, healthcare, transportation, agriculture and consumer technologies. The European Union's 2018-2020 Work Programme included funding for robotics in industry, as well as core technologies such as AI, mechatronics, and model-based design tools.

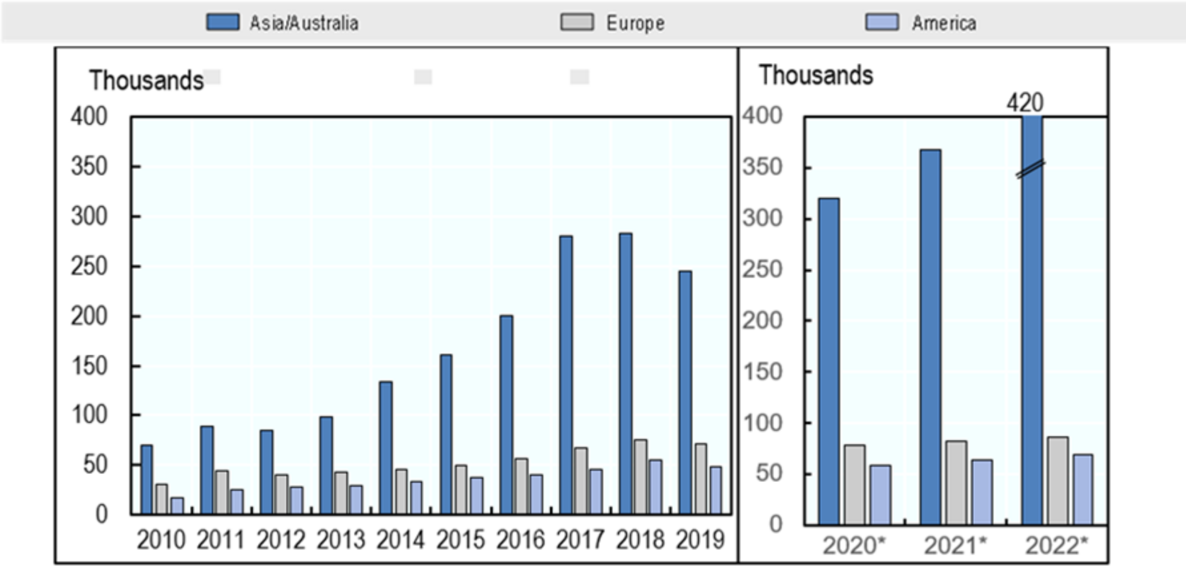
The United Kingdom's 2020 Robotics and Autonomous Systems (RAS) programme aims to capture value across the industrial and innovation system. The RAS Network, established in 2015, has the goal of developing academic excellence, expanding collaboration with industry, and coordinating activities at eight engineering and scientific research facilities, four centres of doctoral training and 30 partner universities.[16]

Although the United States does not possess an overall industrial or automation policy, there have been efforts to develop strategies for robotics, AI, drones and autonomous vehicles. The National Robotics Initiative (NRI) supports robotics R&D. NRI-2.0 focuses on cobots and encourages collaboration between academia, industry, not-for-profit and other organisations, as do the Advanced Robots for Manufacturing Institute and regional robotics clusters. At USD 35 million, the NRI budget for 2019 was relatively small.

Source: Demaitre (2020), "Robotics R&D still driven by government initiatives worldwide, says IFR report", https://www.therobotreport.com/robotics-rnd-still-driven-government-support-worldwide-says-ifr/.

Figure 16. Industrial robot installation by region, 2010-2019 and projections to 2022

A. Annual installation of industrial robots 2009-2019 B. Projections to 2022



Source: IFR (2020), *World Robotics Report 2020.*

Robot uptake in firms

A number of conditions have favoured growing robot uptake in firms. Quality-adjusted robot prices have fallen, and installing robots has become easier, in some cases taking just a few weeks. Pre-engineered solutions that dispense with customized integration have become more widespread. Mobile robots that redeploy easily from one task to another can eliminate costs involved in moving floor-anchored robots. And relatively inexpensive cobots - with humans and machines working together – have expanded the range of tasks that can be automated. However, despite these enabling conditions, the diffusion of robots in firms is highly uneven and often limited. The following observations consider why.

Some robot technologies, while commercially available, are still too expensive for widespread use. The cost of each robot is typically only a fraction of the total investment needed. A general purpose robot arm capable of carrying a payload of less than 10 kg might cost around USD 20 thousand. But spending on installation/integration, safety, tooling and programming could add four to six times that amount.

Uncertainty around the return on investment (ROI) can also hinder adoption. ROIs were easier to calculate for earlier generations of single-function robots on assembly lines. By contrast, new and more flexible robots might be used in many production processes, each of which could be automated to different degrees. Public efforts at technology diffusion could help by providing information on expected ROIs – or the ranges thereof - and how they were calculated. Sweden has established an initiative to this end under its *Robot Accelerator Program*.[17]

Small firms use robots much less than large firms. In Europe, for example, 36% of surveyed companies with 50 to 249 employees use industrial robots, compared to 74% of companies with 1 000 or more employees (Fraunhofer, 2015). In Denmark, in 2018, firms that had adopted robots were on average 2.6 times larger than firms that had not (Humlum, 2019). This size-sensitivity reflects the greater financial resources, experience with advanced production technologies, and economies of scale available to larger firms. Robots that handle small or even single batch sizes are not yet common in industry. Low levels of robot use in SMEs presents a significant opportunity for increasing productivity in OECD economies. Leading adopters such as Germany, Japan, Korea and Singapore possess active public programmes to help firms, especially SMEs, use advanced manufacturing technologies, including robots. Consultation with experts for this report suggests that the content of government programmes aimed at technology diffusion sometimes reflect a lack awareness of the many ways that robots can be used in SMEs.

Diffusion of robots in healthcare

The use of robots in health systems has been constrained by general unfamiliarity with the potential of robots, the high cost of leading-edge robot systems, institutional inertia, and the newness of some applications. Low wages, especially among care workers, also discourage investments in assistive robots.

Among other steps, governments can examine how to accelerate the deployment of existing robot solutions, e.g. by providing platforms that highlight use cases. Publicly reporting technology use by hospitals can accelerate adoption (Skinner and Staiger, 2015). Such reporting should be accompanied with data on efficacy, to help gain acceptance among lay communities, not just trained specialists (CCC/CRA, 2016).

In a crisis, a high level of institutional familiarity with robot technologies could have another positive consequence; it could increase readiness to rapidly repurpose or innovate with currently available robot solutions. This might be quicker and more effective than relying on older robots stockpiled in preparation for a crisis. During the Fukushima disaster, stockpiled robots were reportedly less suitable than routinely used commercial models.[18] Older robots designed for interventions in nuclear facilities had specific capabilities (e.g. radiation resistance and advanced mobility) that were outweighed by their slow speed and limited energy storage.

As discussed in the following sections, a range of other conditions also affect the spread and adoption of robot technologies in industry and services, including education and training, standards, digital connectivity and policies on data and trade.

Education and training

The level and composition of workforce skills are the most critical variables in an institution's ability to adopt new technology that is otherwise cost-effective. Populations with broad and strong generic skills – i.e. literacy, numeracy and problem solving – are better positioned to acquire fast-changing technical knowledge, such as in robotics. More specifically, some countries are rapidly developing curricula relevant to robotics (China, for instance, is developing robotics education tailored to primary schools [Ren, 2016]). Robotics engineering programmes could be embedded in high school curricula.

Companies in many countries report shortages of engineering skills, from mechanical to software engineering. Relevant here are reforms to education to attract more students to STEM fields and help those with interest and talent to flourish. Atkinson and Mayo (2010) review the issues and suggest policy priorities.

Skills needs are also in flux. As robots are deployed more widely, demand will likely rise for roles such as "robot co-ordinators" to oversee robots and respond to malfunctions. Not all robot-related jobs are software jobs. Many concern hardware. Training could help to open such jobs to workers who possess basic mechanical skills (as taught, for instance, in vocational courses). Many of the necessary skills do not require a four-year degree. Shorter courses could help, especially if delivered at scale. In the United States, for example, the 12-week Rockwell programme trains and certifies underemployed veterans as instrumentation, control and automation technicians.[19] *First robotics* (a not-for-profit) aims to inspire young people to become leaders in science and technology, engaging them in mentor-based programs that teach about robotics and other fields of science and technology.[20] In Greece, during the first COVID-19 lockdown, the *Edumotiva Lab* taught children to use and programme robots at home.[21] The challenge is to grow such initiatives, and to incorporate the lessons they provide into mainstream education.

Traditional methods of training surgeons in the operating theatre will need to incorporate robotics and address the growing importance of simulation. This will require new standards for training pathways and new systems of certification and re-certification (Mottrie, 2019).

Standards[22]

Standards permeate the entire field of robotics. Standards are necessary for the machines that make robots, for how robots report data, for robot ontologies, for interoperability, for describing performance testing, for performance, and many other topics. Safety standards are a major concern.

Standardisation and its processes affect the development and diffusion of robots in a number of ways. A first issue is the aptness of standards in a context of rapid technical change. Technical standards are built around consensus and take years to develop. Expert opinion suggests that current standards for safety-related control functions are outdated in the new environment in which AI-equipped robots perform safety-critical tasks.

The current method of domain-specific standards may not serve robotics well. For example, standards have developed for industrial robots, mobile robots, healthcare robots, agricultural robots, and robots in services. This runs counter to the multi-purpose nature of robotics and robots, and is reported to create a mix of standards and regulations that is sometimes confusing and contradictory. For instance, roboticists observe that the limits on collision force and energy should be the same regardless of the setting a robot is used in (a greenhouse, a cleanroom, delivering packages, etc.). The standardisation community is aware of this situation, but has yet to act in a meaningful way, with the consensus-based process slowing progress (although some processes unrelated to safety move more quickly).

Standards are essential to reduce uncertainty. In general, SMEs are the least equipped firms to bear uncertainty. But SMEs often struggle to access, interpret and use standards. They frequently lack the resources to send colleagues to standards-development meetings, to shape the discussion and to purchase standards. Governments can facilitate the participation of SMEs in standards processes. This is an aim of the France-Germany-Italy trilateral Cooperation on advanced manufacturing, begun in 2017.[23] Governments can also gather the views of SMEs working in robotics and transmit these to standardisation groups (see for example the COVR project (www.safearoundrobots.com)). However, the process can be slow, and doesn't ensure that feedback from SMEs is acted upon.

Beyond formalised standardisation processes, many commentators observe that progress in robotics would be helped by open-source community-vetted platforms focused on system interoperability and synergistic technical tools (e.g. in programming, hardware and communication). Such plug and play frameworks would let research groups focus on their specialised subtopics while contributing to community-wide efforts (CCC/CRA, 2016).

Data policies

Data policies can also aid robotics. Governments can help fund the development of data useful to robotics, facilitate data sharing and support open data in (robotics-related) science (the *OECD Principles and Guidelines for Access to Research Data from Public Funding* provide an overarching framework for policy in this connection[24]). Researchers in Spain recently released a dataset of millions of frames that show robots moving through and manipulating objects in virtual rooms. Such data help to solve robot vision problems. Public funding could help develop and share useful data in application areas relevant to public services, such as health and education. This would be particularly useful for niche applications where data samples for training robot systems are otherwise (too) small. The EU has also acknowledged the benefits of developing big data environments by issuing the Regulation on the free flow of non-personal data. This Regulation aims at removing legal and technical obstacles to the free movement across the EU of non-identifying data.

Policymakers should examine the effect on robotics of restrictions or uncertainty in data collection. Social, delivery, emergency or other robots often require training in public spaces open to random passers-by. If a robot system behaves unexpectedly, engineers need to review the data and possibly retrain the AI. But roboticists face uncertainty if images require individual consent (for instance under GDPR rules). To comply, researchers might adapt their images, for instance by blurring them. However, this can reduce the data's usefulness for training. Researchers might seek consent from the persons filmed, which in the case of GDPR would also require creating mechanisms such that, if someone at any time wished to be forgotten, the researchers could locate person-specific images and anonymize or remove them. These circumstances create considerable uncertainty and cost for development, innovation and possibly competitiveness. Evidently, policy must weigh these eventualities against other societal priorities.

Robots also raise issues of individual privacy. A future medical robot might gather data on a patient, but be unable to obtain consent if the patient has diminished awareness. Challenges could also arise in identifying a data controller – the person or body responsible for gathering or processing personal data. For instance, if a care-home robot collects medical data, the data controller could be the patient's doctor. But the data might also be processed in the cloud, with multiple possible controllers. Beyond medical data, a robot in a care facility or domestic setting could also gather sensitive personal data, e.g. on religious or political views. A further complication is that, technically, such data can be shared across robots or with third parties.

Digital connectivity

Digital connectivity, particularly 5G broadband, is increasingly important for robotics. 4G systems will not allow streaming of video at 200 megabytes per second. 5G will permit much richer data streams to and from robots, for instance combining auditory and visual data, and will allow for network slicing (so independent networks can operate on the same physical infrastructure). However, the role of 5G is intimately linked to where robots use AI (for sensing, interpretation and/or acting). The consensus is moving slowly towards embedded or edge AI, where traffic might be offloaded to fixed networks, also benefiting from the development of the new WiFi 6 standard. Cloud computing will grow in importance, for cloud-based learning, for routing multiple heavy video streams to distant locations, and for some forms of fleet learning (where scenarios encountered by robots, with the associated sensor data, are shared).[25]

Fibre-optic cable has characteristics critical for some robot uses. For the emerging field of remote surgery, the low signal latency that fibre-optic cable provides, along with symmetrical upload and download speeds, are essential: the time between a surgeon's movements and a distant robot's response, and the return signal to the surgeon, must be as short as possible (see the *OECD Recommendations on Broadband Connectivity* (OECD, 2021b)).

Robot leasing - and the robots-as-a-service business model - has advantages for some firms, especially SMEs. These include avoiding expenditures on fixed capital and robot operators, and receiving automatic upgrades. The market for robot leasing is growing. Factors that affect the size of a robot leasing market include: the ease of integrating robots into production; the ease with which robots can be programmed; and, the cost of robots. Cloud connectivity could facilitate robot leasing (owing to cloud-based learning). However, low rates of cloud use among firms in some countries might hinder this market.

Many steps are open to governments to support digital connectivity (OECD, 2020; OECD, 2019b).

Regulation

The regulatory implications of robotics will become increasingly complex, owing to expanding robot capabilities, new domains of use, and novel forms of human-robot interaction. Regulation has three main goals, i.e. to provide producers with certainty, protect consumers, and facilitate innovation. The aim is to create a regulatory framework that best balances all three goals. The space available in this paper does not allow reviewing the differences in law across jurisdictions, the intricacies of legal scholarship, and the comparative merits of competing legal proposals. Thus, this section only touches on some main challenges, drawing heavily on Holder et al. (2016).

An obvious concern is that robotics changes faster than regulatory frameworks. While existing laws are often adequate to resolve potential legal disputes arising from the use of robots, some changes may be necessary. For instance, while it is technically feasible for a surgeon to operate on a patient in another country, legislation does not yet stipulate which country's laws would apply in the case of a mishap (a problem that also pertains to tele-health more generally).

Robots with a humanoid appearance raise another issue which regulation may need to address. If people unconsciously attribute a high degree of agency to humanoid robots, then they might be less prone to questioning the instructions or behaviour of such systems (in fact, people readily attribute agency or intentionality to artefacts that do not appear human at all, such as a table lamp programmed to move in human-like ways[26]). This could have implications for consumer protection, because consumers might overly trust robots with humanoid features, becoming more susceptible to misleading information. For the same reason, the safety of some critical systems could be impaired if human operators have to work with systems that have a human-like appearance. While too early to judge, as yet, safeguards might eventually be needed such that robots are not overly anthropomorphic.

A central question for wider robot use - and the insurance industry – concerns legal liability. The major legal conundrum relates to machine learning in the field. Today, if an unintelligent robot is programmed incorrectly and harms someone, liability lies with the user, not the robot manufacturer. In the case of robots with AI-enabled control functions two possibilities exist:

1. The robot goes to school before being deployed (i.e. learning takes place at the manufacturer).
2. The robot learns during operation, including learning new tasks not imagined by the manufacturer.

Option 1) presents a technical challenge for manufacturers as they ponder how to guarantee that the learning process will not produce unforeseen consequences in real-world environments without testing the robot exhaustively in every conceivable situation.

Option 2) may be simpler, provided the issues under the first option can be solved. Clearly, the manufacturer cannot be held responsible for the robot's actions if it does not control the environment in which the robot is used, the situations it learns from, and so on. A possible solution might be to certify a robot's baseline learned capabilities. However, once the user unlocks a learning process, the warranty would become void.[27]

Legal scholars are debating a wide variety of additional liability-related questions. For example, might damage to ever more intricate medical exoskeletons and intelligent prosthetics one day confer a right to claims of bodily harm, with implications for compensation and insurance? Should it become a legal requirement that surgeons receive formal training to operate surgical robots? Might responsibility for harms become harder to attribute because of algorithmic inscrutability (at the time of writing, the EU is considering whether to alleviate - and in certain cases reverse - the burden of proof for damage caused by AI-driven robots and applications) ? (the OECD is currently working with independent experts to develop practical guidelines for implementing the OECD AI Principles; among other topics, it is examining how regulatory authorities can best address the challenges raised by AI).[28]

Autonomy levels for road vehicles exist on a scale from 1 to 5. For medical robots, there exists no established definition of autonomy levels (Yang *et al*., 2017). Such a definition is complicated to achieve: the range of tasks, working environments, technologies and risks to be considered is much greater than for road vehicles. A definition of autonomy levels would provide a basis for allocating different technologies to different regulatory approval procedures, which vary in stringency, cost and time. A categorisation of autonomy for medical robots is necessary for the entire sector (Yang *et al.*, 2018).

It is also important to examine whether regulation hinders new robotic solutions. In a crisis, such as the COVID-19 pandemic, regulation for some robot applications might justifiably lower liability for innovators and de-emphasize risk avoidance. A case in point could be regulation of robotic delivery systems, which present fewer safety concerns if a population is in lockdown.

Lastly, complex regulation can hinder robot adoption, particularly in SMEs, which typically lack a team specialising in regulatory compliance. Some countries possess public programmes to help SMEs deploy robots when regulation is hard to interpret. However, a better solution would be to begin with more amenable regulation.

Regulatory sandboxes for robotics

Regulatory sandboxes help governments and industry better understand the regulatory implications of new technologies. They do this by providing a limited form of regulatory waiver or exceptional regulatory flexibility for firms to test new products, services or business models in a live environment. They are especially relevant for highly regulated sectors such as financial services and healthcare. Indeed, regulatory sandboxes have mostly focused on Fintech (Attrey *et al.* 2019). Evaluations of the impacts of regulatory sandboxes are sparse, and few countries have used sandboxes for robotics. Singapore, however, has adopted a mix of sandboxes, test beds and technology pilots for robots in long-term care, an area of use that raises various technology risks and ethical questions (Tanand and Taeihagh, 2020). The overall impact of such measures merits further study. A further consideration for policymakers is that selection processes for regulatory sandboxes should avoid benefiting some companies at the expense of others.

Establishing a robot commission?

The legal scholar Ryan Calo has argued for a national Commission for AI and Robotics for the United States (Calo, 2014). In Calo's view, such a Commission could advise on issues at all levels — state and federal, domestic and foreign, civil and criminal — relevant to unique aspects of AI and robotics and the novel regulatory and other implications they bring. The merit of such a governance arrangement, Calo contends, is that insights in one domain of use can be relevant to others, making learning across government more efficient.

Others hold that robotics and AI do not form special cases and that existing agencies and authorities, including tort law, have the capability of dealing with most if not all the issues raised, perhaps with some adjustment.

Digital security and robot systems

The OECD's policy work on digital security is relevant to robotics. The key texts are the 2015 *Recommendation on digital security risk management* (https://oe.cd/dsrm), the 2019 *Recommendation on digital security of critical activities* (https://oe.cd/dsca2019) and the 1997 *Cryptography Policy Guidelines* (https://oe.cd/crypto). New technologies might aid robot security. A recent example is work to achieve consensus in robot swarms, for instance for path selection, spatial aggregation and collective sensing. Malfunctioning or malicious robots can make it impossible to achieve consensus using classical protocols. But Strobel *et al.* (2020) show that a swarm of robots can achieve consensus using blockchain technology, even in the presence of rogue robots. Still, robot swarms will remain vulnerable to other types of attack. For example, AIs could provide misleading external cues to the swarm, attempting to trigger harmful emerging behaviours.

Tax policies

Many countries that lead as robot adopters use tax incentives for manufacturers to invest in advanced technologies, including robots. South Korea provides a tax credit for investment in new equipment, and Japan, Slovenia and the United States permit accelerated depreciation on new equipment (Atkinson, 2019). As of January 2021 the Polish government allows firms an income tax deduction of 50% of the cost of their investments in robots. The measure will last for five years (Obara, 2020). Little if any research exists on the effects of tax policies on robot adoption across countries or across firms of different size. However, there is general consensus in the economics literature that first year expensing – offsetting an item of expenditure against taxable income - does lead to faster rates of expenditure on capital investment. Accordingly, given the impacts of robots on productivity, first year expensing or even investment tax credits on machinery, including robots, will help (as a rule, from the standpoint of the firm, expensing an investment is superior to a depreciation allowance because money has a time value, and for an expensed item the deduction occurs in the current tax year. The money saved becomes available for immediate use).

6. Conclusion

This paper has reviewed recent advances in key areas of robotics research and technology, current and emerging uses of robots, their diverse economic and societal impacts, and the relevant science and technology policies and priorities. Owing to the COVID-19 pandemic, emphasis has been given to robots in healthcare. At the time of writing, robots had played a growing but still minor role in the pandemic. However, with the right policies, and with technological progress, robots could be more prominent in the response to future outbreaks of infectious diseases. Robots could also play important roles in society's efforts to cope with the long-term health challenge of population ageing.

Equally important will be the contribution of robots to raising the rate of growth of labour productivity, one of the main economic challenges facing OECD countries.

As robots become more diverse and intelligent, people will interact with them in new and useful ways, and in ways that could significantly improve quality of life. However, so far, the potential of robotics is largely untapped. As this paper has sought to illustrate, governments possess tools with which to shape future developments and speed the uptake of socially beneficial robots.

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Annex 1. Grand challenges in robotics research

Research subject	Challenges
New materials and methods of fabrication *For new multifunctional, power-efficient autonomous robots*	Materials with novel properties, along with new fabrication technologies, will help to build more capable robots. Progress is needed to develop: -Materials able to adapt and heal over time in ways that mimic the complexity in some natural systems. -Techniques that can build structures from the micro- to the macroscopic, for example by combining additive manufacturing, self-assembly, magnetic assembly, assembly from ori- and kirigami principles, freeze-casting (for fabricating porous materials), low-cost casting in vacuums, laser engraving, moulding processes in which actuators are embedded in the moulded piece, etc.. -Techniques to create features and structures that vary in size over nine orders of magnitude using multiple materials.
Sensors and perception *For better and smaller sensors of multiple variables (pressure, motion, heat, etc.), with better processing of sensor data.*	Improved sensing and perception is key for many desired robot functions. Beyond visual sensors, it will be impossible to achieve other manipulation goals (grasping, making surgical incisions, etc.) without advances in tactile and related sensing. Biomedical research at the University of Southern California led to the BioTac® sensors, one of the first sensor technologies to endow robots with the ability to replicate, and sometimes exceed, the human sense of touch. The biomimetic sensors – which sense pressure, temperature, vibration and other stimuli – are critical for advanced prosthetic, among other uses. - More research is needed for better and smaller sensors, along with the algorithms that process the data and produce useable information to guide actions (see the section in this table on AI). - Robots also need to perceive three-dimensional models of the world for better navigation and manipulation. These models require tagging with semantic information about objects, their properties and uses, and features of the environment. Today's robots are good at understanding where things are located in the world, but have little or no understanding of what things are (CCC/CRA, 2016).
Power and energy *For robots that can operate independently over long periods of time.*	Batteries do not match the performance of metabolic energy generation in living organisms. Progress is needed to: -Increase battery lives, raise their energy densities, reduce battery weight, improve heat tolerance, and improve the radio-isotopic systems currently used in satellites, space probes and other applications that require long-term autonomy. -Enable robots to harvest energy from sources as diverse as solar light, ambient heat, piezo-electrics (when electric charge is generated in solids subjected to pressure), and mechanical vibration, among others. -Actuators do not currently match those in animals, especially at small scales. No robot system rivals the flexibility and dexterity of a human hand, for example. Improvements in already existing artificial muscles could help revolutionize the field.
Robot swarms *For simple, cheap robots to function as teams that can match the performance of larger, task-specific robots.*	The most useful swarms could be those that combine robots with complementary abilities (such as aerial and ground systems). Progress is needed to: - Mathematically model robot groups, especially heterogeneous groups, optimally design groups and their behaviours (and deal with emergent behaviours). - Design multidimensional feedback loops across large groups. - Engineering tools and methods to program and effectively deploy software over heterogeneous robot systems (different robot generations, types, configurations, etc.).
Navigation and exploration in extreme and unmapped environments *For robots to traverse difficult unfamiliar environments, adapting*	Some robots may need to navigate complex environments, such as narrow obstacle-strewn spaces with limited possibilities for perception (in the dark or under the sea, where radio signals do not penetrate, etc.). Progress is needed to develop: -Greater on-board intelligence using multi-input data (visual, tactile, auditory, etc.). -Higher bandwidth and lower latency communications, to reduce on-board energy and computing

and learning in real-time.	constraints. - Progress is needed in autonomous manipulation, such as grasping and manipulation in open, changing unstructured environments. Systems are needed that use prior knowledge and models of the environment, but do not fail catastrophically if such prior knowledge is unavailable (CCC/CRA, 2016).
Artificial intelligence and formal methods	AI systems are needed that know how to interact, seek help, recover from failure, and improve over time. Progress is needed to develop: -Systems that can detect and use input from their own subcomponents (for instance with edge devices teaching every other edge device), model their combined operations, and modify those models if change occurs in the robot's structure. -Systems that comprehend deeply and synthesize across domains and types of data/information. This applies, for example, to a robot's action (what to do, how and when), motion plans (path planning as well as control of mobility actuators or grasping effectors), and execution (navigation, etc.) that responds in real-time to changing conditions (such as recognizing that the robot dropped a part and needs to correct this). At present, robots still have problems in navigating complex or changing store layouts over a long period with minimal or no human intervention (CCC/CRA, 2016). Systems made up of heterogeneous AIs or robots that integrate easily and reliably over time (initial examples exist of cloud AIs that share knowledge). -Methods to ensure the safety of AI systems when interacting with the physical world. -Progress is needed in mathematical approaches to formally specify systems and their behaviours (collision avoidance algorithms, for example, have been formally proven). Progress will form the basis for certifying robotic systems, ensuring the safety, security and predictability of robots, including robot reporting to humans about possible system failures and automatic deployment by robots, if necessary, of strategies for gradual and safe system failure, rather than catastrophic failures (CCC/CRA, 2016).
Brain-computer interfaces *For seamless control of peripheral neuro-prostheses, functional electrically stimulated devices and exoskeletons.*	Current means of sensing and data acquisition through interfaces with the brain are expensive and cumbersome. Progress is needed to develop: -Micro-scale implantable sensing systems with very low power needs for data processing. -Wireless ergonomic communication devices, which could permit untethered implants for patients. -Improved data processing that accounts for patient-specific cortex folding and functional maps. -More accurate brain-computer interfaces external to the body.
Social robots *For robots to integrate with human social and moral dynamics and norms.*	More useful robots in hospitals, schools and other environments will need to possess more social attributes. Progress is needed to: -Better model social and moral norms and dynamics. -Improve perception and understanding of social cues such as gaze direction and vocal intonation. These cues can be subtle, ephemeral, embedded in and qualified by other signals (a shrug, a grimace, etc.), and be culture and context dependent (for example, the meaning of the same string of words in one context might differ in another). -Social interactions are often not one-time encounters, but can recur with the same individual over months or years. So robots will need to be able to improve and maintain (possibly over years) models of an individual's knowledge, beliefs, goals, desires and emotions.
Ethics and security *For responsible innovation in robotics.*	Robotics and AI raise a variety of legal-ethical issues, the scope of which is likely to grow as these systems acquire new capabilities. Progress is needed in: -Understanding how intelligent robots change the attribution of human responsibility (what, for instance,

	does joint robot-surgeon control imply for tort law in medicine?) -Using AI to improve security by increasing systems' ability to endure, avert and counter attacks (for instance, in the latter case, after identifying the vulnerabilities of hostile systems) (section 5.8). -Understanding a full spectrum of safety limits when robots come into contact with populations in real-world environments, which differ from more standardised industrial environments (e.g. looking beyond healthy individuals over the age of 18, towards infants/children, animals, physically or cognitively challenged individuals, etc.) For example, There are currently no valid force and power limits in any standards for robot interactions with children in any standards. The limits in standards are currently only available for healthy adults, aged over 18. Everyday life, furthermore, is messy, unstructured and unpredictable.

Source: Yang *et al*. (2018), CCC/CRA (2016) and consultations with multiple roboticists.

Endnotes

[1] Colin Angle, CEO and founder of iRobot. Interview with Lex Fridman, 19 September 2019, Artificial Intelligence podcast. https://lexfridman.com/colin-angle/

[2] Named after the roboticist Hans Moravec.

[3] Justine Cassell, a Professor at Carnegie Mellon University, kindly informed the author that the question of whether robots that have a physical instantiation occupy a unique space in people's imagination is still hotly debated. While people attribute human-like attributes to robots, it is unclear if they attribute human-like attributes only to robots. For example, research by Byron Reeves and Clifford Nass has shown that people avoid giving feedback on a computer's performance in ways that indicate they don't want to hurt its feelings. People also react to embodied conversational agents (ECAs), portrayed in lifelike size on a screen, in the same ways they react to real people (nodding, pointing, looking into the eyes of the ECA, etc.) (Cassell and Thórisson, 1999; Nakano, *et al*., 2003).

[4] See https://www.bostondynamics.com/

[5] See http://news.mit.edu/2013/mit-cheetah-robot-0308

[6] Computational psychiatry uses theory, AI and other techniques to relate data on neuro-biology, environmental factors and mental states.

[7] Thanks are due to Justine Cassell for drawing the author's attention to the insights in this paragraph.

[8] https://www.darpa.mil/program/agile-teams

[9] The author is grateful to Mr.Nobuhiro Muroya, of the Nuclear Energy Agency, for this information.

[10] It is unclear however if the physical robot would also outperform an ECA on a tablet or an ECA of the same size as the robot. The comparison is of interest because, among other things, ECAs are cheaper and safer than physical robots. Thanks are expressed to Justine Cassell for drawing the author's attention to this point.

[11] In industry, Airbus is developing a wearable soft-frame robot, or exoskeleton, to help workers manipulate loads ergonomically.

[12] See, for example, the recently developed Moley kitchen robot at https://www.moley.com/

[13] Communication from the authors. For further information see: https://aparc.fsi.stanford.edu/research/impact-robots-nursing-home-care-japan

[14] https://www.eu-robotics.net/

[15] For instance, children who grow up in areas with more inventors are more likely to become inventors (Bell et al., 2019). A study of successful inner-city firms in the United Kingdom found that almost half the entrepreneurs surveyed had immediate family members who had owned a business (Ramsden *et al*., 2001). One study found that people who just know an entrepreneur are more than twice as likely to enter business as those who do not (Reynolds *et al*., 2001). Audretsch *et al.* (2002) also showed that the commercialisation of research brought about by the Small Business Innovation Research programme in the United States induced other scientists to attempt entrepreneurship.

[16] ukras.org

[17] See https://tillvaxtverket.se/amnesomraden/digitalisering/robotlyftet.html

[18] Thanks are due for this observation to Jose Saenz, from the Robotic Systems Unit at Fraunhofer IFF, and a Director of euRobotics.

[19] See https://www.rockwellautomation.com/site-selection.html.

[20] See www.firstinspires.org

[21] See http://edumotiva.eu/edumotiva/

[22] Thanks are due to Jose Saenz, whose insights are the basis for this section.

[23] https://www.plattform-i40.de/PI40/Redaktion/EN/News/Actual/2018/2018-01-18-trilaterale-kooperation.html

[24] The full text of the *Principles and Guidelines* is available online at www.oecd.org/science/sci-tech/38500813.pdf

[25] Thanks for this observation are due to Gregory Ameyugo, Head of Ambient Intelligence and Interactive Systems at France's *Atomic and Alternative Energies Commission*.

[26] See Guy Hoffman's 2013 TED talk "Robots with soul", https://www.ted.com/talks/guy_hoffman_robots_with_soul?language=en

[27] Thanks are expressed for this observation to Gregory Ameyugo.

[28] https://oecd.ai/