Mid-cycle Update to the US National Robotics Roadmap[1]

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1. Introduction

This is a mid-cycle update to the US National Robotics Roadmap. The last regular update was in September 2020 (Christensen et al., 2020) and the next regular update to the full document is planned for 2024. The world has changed significantly since the last release. The COVID pandemic has ended, there is another administration in Washington, the National Robotics Initiative has officially ended, and the political climate for international trade is constantly changing. Given all these aspects, a minor revision of the roadmap was proposed by the Computing Community Consortium (CCC). The process is that we published a call for contributions that have all been reviewed and integrated into the present document. The list of contributors is listed at the end of the document (Section 6). In addition, a discussion session

[1] The mid-cycle update to the roadmap has been facilitated by the Computing Community Consortium (CCC). The support is gratefully acknowledged.

was organized at AAAI in Washington, DC on February 7th to collect input from the AI/Robotics community. All inputs have been considered in the preparation of the present document.

The National Robotics Initiative (NRI) was created in 2011 by President Obama as a cross agency program involving National Science Foundation (NSF), National Aeronautics and Space Administration (NASA), National Institute of Health (NIH) and United States Department of Agriculture (USDA). In parallel, an inter-agency steering group was set up and coordinated through the Office of Science and Technology Policy (OSTP) within the White House. The program also involved a specialist in OSTP to work with the director of Science and Policy towards the implementation of the program. Today there is no cross-agency program and a few agencies have their own program with limited cross coordination; the emphasis has shifted more towards a National AI program.

NSF used to be an anchor tenant in the NRI program. Today, the program has been replaced by the NSF Foundational Research in Robotics (FRR) program, which is focused on robot systems that include both computational and physical complexity. Robotics is the integration of embodiment/physical interaction with the world, sensing, and perception to interpret the external world and intelligence/planning to enable engagement with the world through its embodiment. The interaction is both direct physical engagement with the world and communication with other (intelligent) agents in the environment, such as humans. The new FRR program is very much about the intersection of embodiment, perception and intelligence, but without direct support for component technologies within each of the areas of embodiment, perception, and planning. Consequently, many researchers in robotics and component disciplines do not have a natural program within NSF (CISE or ENG) to consider for their basic research.

A number of robotics programs also exist within Department of Defense (DoD). The Army Research Lab (ARL) and Office of Naval Research (ONR) have programs, but mainly with clear mission objectives rather than curiosity-driven objectives. In addition, the number of performers is still modest. NIH also has programs with clear clinical objectives. In general, acceptance rates for NIH are very low. There is significant progress on design of medical devices, support for elderly people and for medical procedures. However, during the process from idea to a certified product/method, the risk of losing support is significant.

Over the past decade, national support for basic research in robotics has been significantly reduced. This is at a time when Europe (EU-Horizon), China (Robotics+), South Korea (RRI), and India (Manufacturing in India) are all investing heavily in the technology. Already today, the US is falling behind other nations in terms of basic research and utilization of robot technology for next-generation manufacturing, logistics, and smart infrastructure. When the NRI was launched in 2011, the US was a top 5 consumer of robots for manufacturing and China was not in the top 10. Today China is the largest consumer of robots for manufacturing, and the US is now 7th according to the International Federation of Robotics (IFR, 2022). Without a concerted investment across basic research, translation and utilization, more ground will be lost.

2. Megatrends

2.1 Manufacturing

Over the last five years, the world has seen major changes in manufacturing. More and more manufacturing has been re-shored to America. There are multiple motivations for this change. Foremost, many products are seeing mass customization: i.e., each product is customized for a single customer, which makes mass manufacturing less practical and one may as well produce the product close to the customer. In addition, there is a desire to reduce delivery time, which again motivates proximity to the customer. The U.S. also experienced major supply chain disruptions during the COVID pandemic. Over the past 5 years, we have seen 1.5 million new jobs created in the manufacturing sector (BLS, 2023) and also a significant increase in robot use (IFR, 2022).

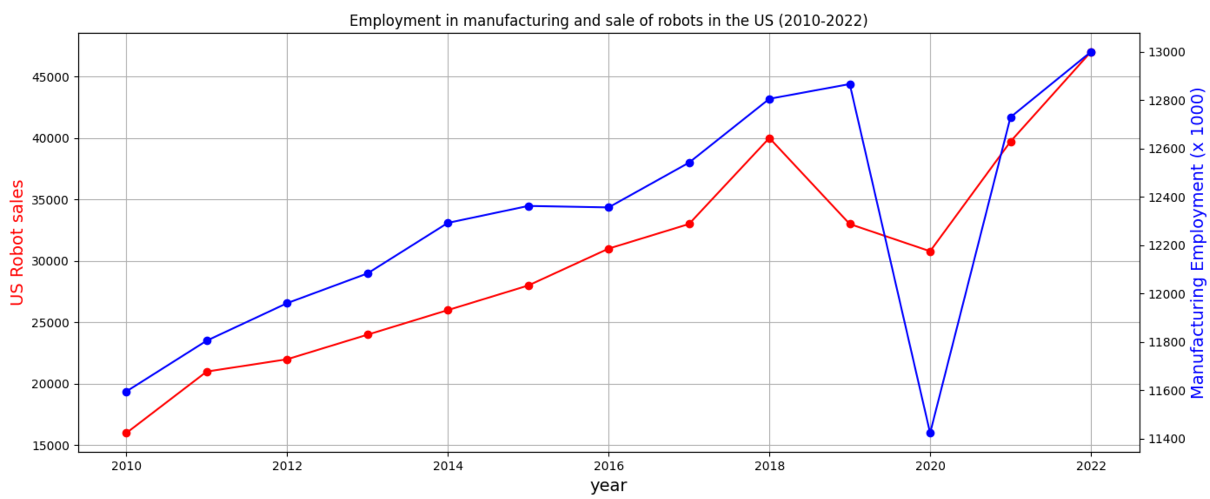

Figure 1. Employment in Manufacturing over time and robot sales during the same period (2010-22) (Source: BLS, 2022 and A3, 2022)

A decade ago, the concept of collaborative robotics gained traction with the introduction of robot arms that can safely co-exist with people in the same space for tasks such as tending to machines, joint handling of heavy objects. Today, close to 15% of all manufacturing applications utilize collaborative systems and this is an area where the most significant growth is experienced as it opens entire new opportunities.

The US used to be one of the top countries in terms of density of industrial robots. Over the last two years, China has overtaken the US in density for manufacturing. Density is here defined as the number of robots deployed per 10,000 workers. In China, there are 322 robots deployed per 10,000 workers, whereas the US has 274 per 10,000. The number of units sold in China is almost four times larger than the US and growing fast. Consequently, the US is falling behind

China and other countries such as South Korea, Japan, and Germany in utilization of robot technology.

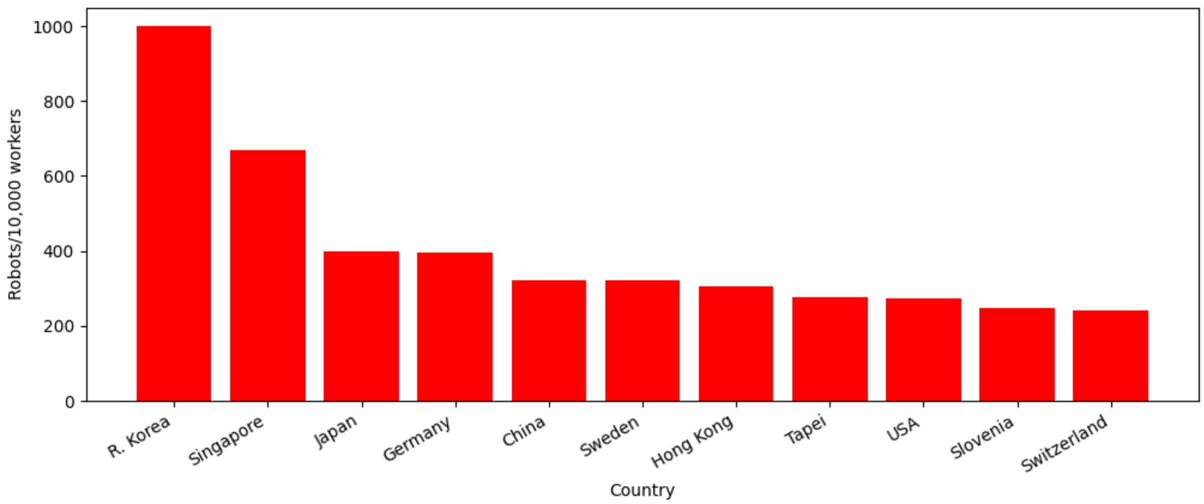

Figure 2. Robot Density (number of robots / 10,000 workers) in manufacturing (Source: IFR, 2022)

2.2 Logistics / Material handling

The COVID-crisis gave people a period at home and often people did not go to grocery stores or other retail stores. During early 2020 there was a 33% increase in e-commerce sales in the US (US Census, 2023). Services such as DoorDash, Uber Eats, GrubHub, Amazon Prime, saw a doubling in growth. In general, e-commerce sales have doubled since 2019 and continue to change retail business. As there is a need to deliver fast and with a broad selection, there is also a change in business infrastructure. It used to be that major distribution centers allowed for order completion with pick-up, packaging, and van delivery to the customer. Now these mega-warehouses are complemented by micro-fulfillment centers that are much closer to the customer, but have a reduced assortment of articles (Stock Keeping Units - SKUs). Micro-fulfillment centers are estimated to have a consolidated average growth rate (CAGR) of 44.8% over the next ten years (Logistics IQ, 2022). It is no surprise that robots are playing a major role in these fulfillment centers as KIVA / Amazon demonstrated that it is possible to increase worker efficiency by almost two orders of magnitude. Newer companies such as Symbotic and Berkshire Grey have verified the growth projected by Amazon and KIVA.

2.3 An Aging Society

The world is growing older: the world median age increases about 8 hours every day. The dependency ratio (people < 15 and > 64 compared to the working age population (15-64)) is already 71% in Japan and most of the industrialized world is above 65%. As healthcare and working conditions improve, people live longer, while fertility rates are declining. There is thus a need to provide quality of life support to people as their physical and mental abilities decline.

Robots offer an opportunity to give people autonomy for an extended period of time for basic functions such as getting in/out of bed, personal hygiene, preparing meals, participation in social activities and rehabilitation. Today, more than 30 million autonomous vacuum cleaners have been sold worldwide, whereas robots with any level of manipulation capabilities for human assistance in private spaces are non-existing.

As the proportion of the working age population decreases, robots can also be used to help people stay in the workforce. Many exoskeletons, both passive and powered, have been developed to help people in their jobs, in the military, and in their lives, for people without and with disabilities. Research in adaptable controllers will lead to as-needed assistance, requiring less battery power and allowing a person to work to their capability at any given time. Beyond exoskeletons, collaborative robots could allow people to stay in the workforce after an injury or as they age. For example, jobs can be created by the development of remote monitoring or teleoperation of robot systems at construction sites.

Tremendous growth has been seen in the use of surgical robots. Initially, they were deployed to reduce the level of trauma associated with surgery similar to laparoscopic surgery, but with improved ergonomics and better control. Recently, other applications such as orthopedics and oncology have also seen major growth in use of medical robots. The cost has been reduced, and the training has picked up to enable much broader access to these tools.

2.4 Sustainability

Multiple initiatives on sustainability have been launched recently, with the aim of promoting sustainable development, protecting the environment, and addressing climate change. Some key initiatives on sustainability include:

1. Sustainable Development Goals (SDGs): The SDGs are a set of 17 goals that were adopted by the UN General Assembly in 2015, with the aim of ending poverty, protecting the planet, and ensuring prosperity for all. The goals cover a wide range of issues, from reducing inequality and improving education, to promoting sustainable cities and communities and acting on climate change.
2. Paris Agreement: The Paris Agreement is an international treaty that was adopted by the UN in 2015, with the aim of addressing climate change by reducing greenhouse gas emissions. The agreement commits countries to limit global warming to well below 2 degrees Celsius above pre-industrial levels, and to pursue efforts to limit the temperature increase to 1.5 degrees Celsius.
3. United Nations Environment Programme (UNEP): UNEP is the leading global environmental authority that sets the global environmental agenda, promotes the coherent implementation of the environmental dimension of sustainable development within the United Nations system, and serves as an authoritative advocate for the global environment.

These are just a few examples of initiatives on sustainability. Robot technology has the potential to assist with monitoring the climate, optimizing the use of pesticides, producing more food, sorting recyclables, and providing surveillance of our natural resources, to mention a few.

3. Research Challenges

Where are we today? What are some concrete challenges?

3.1. Robot Science

Fundamental research is necessary to make the next great leaps in robotics science and applications. Without investments in research to discover new methods for actuation, manipulation, sensing, power, and computing – often as individual components, we will continue to be working with the hardware of today – and its limitations – decades from now. Research funding for new materials could lead to miniaturization, new application domains, better human-robot interaction, and more capable systems.

There are many cross disciplinary research challenges in robotics, but some of the most important ones include:

1. Perception: A key challenge in robotics is developing systems that can perceive the world around them accurately and efficiently. This includes developing algorithms and hardware that can accurately sense and interpret the environment, such as cameras, LIDAR, and other sensors. Simultaneous Localization and Mapping (SLAM) has made significant progress, but mainly using purely geometric models. Machine Learning (ML) has enabled recognition of much larger sets of objects, we are far away from robust perception in general settings.
2. Manipulation: Another challenge is robotic systems that can manipulate objects with the same dexterity and precision as humans. This requires developing advanced control algorithms, grippers, and other hardware. There is a tremendous potential to integrate in new lessons from material science to build more flexible and better sensorized end-effectors as an example.
3. Mobility: Mobility is another key challenge in robotics, particularly for robots that need to operate in complex or dynamic environments. Developing robots that can move quickly, safely, and efficiently, and can adapt to changing conditions is critical.
4. Learning and Adaptation: Another challenge is developing robots that can learn from their environment and adapt to new situations. This requires developing advanced machine learning algorithms and hardware that can enable robots to learn from their experiences and make decisions based on that learning.
5. Human-Robot Interaction: Finally, an important challenge is developing robots that can interact effectively and safely with humans, particularly as more robot systems are deployed in our world. This requires developing advanced control algorithms and hardware that can enable robots to understand human gestures and commands, and respond appropriately – and to anticipate how to interact with untrained bystanders. It also requires advances in cognitive science to build systems with a much more in-depth

understanding of humans. One such area is in the integration of language-based models into robotics.

The key basic research challenges in robotics are to develop robots that are intelligent, versatile, and able to operate effectively in a wide range of environments and situations.

3.2. Robots with Jobs

Today, there is only about one robot for every 40 employees at the best of places in manufacturing. As mentioned before, 80% of warehousing has no automation. Design of robots for the returning manufacturing sector requires a new generation of collaborative robots. Today, almost all end-effectors are engineered to the task at hand. Research on new materials offers an opportunity to design end-effectors that are fully sensorized, which can increase dexterity, reduce cost and engineering requirements. Current industrial robot applications cannot use deep learning as part of their safety system. It is not at present possible to safely certify systems that leverage deep learning. There is a need to do research on methods that can be certified and also study systems engineering to still expand the possible use-cases for robots in industry.

The workforce is shrinking and there is a need for people to remain in the workforce for a longer period of time. This also implies there is a need to consider assistive devices such as exoskeletons. Products have started to emerge, but there is still a need for research on human-robot interaction to ensure fluency in interaction. Building effective exoskeleton systems requires improved actuators, intent estimation, bio-sensors, and high-bandwidth control, in addition to user-studies to consider usability across a broad range of use-cases.

The world needs another 5 billion housing units to provide a safe residence for the world population (WEF 2022). Very limited progress has been achieved in the construction sector over the past 25-years. There are opportunities to modularize building components, to provide ad-hoc manufacturing similar to 3D printing, and to provide mobility support for transport of heavy objects such as glass panels, wall sections, etc. These are all great examples of how robotics and automation can be leveraged to improve productivity and ergonomics.

As mentioned earlier, there also is a need for fundamental research into safety and certification. This includes research on mechanisms to ensure safe interaction with the human users and bystanders. In addition, present methods for deep learning are not accepted by OSHA as a basis for certified safety mechanisms. One approach is to study alternative methods for safety and another is to study design of ML methods that can be certified. It would seem both approaches warrant further consideration.

3.3. Environmental Robots

The use of robots in environmental management is a rapidly evolving field, and there are many exciting developments taking place. One of the key advantages of using robots is that they can operate in environments that are difficult or dangerous for humans to access. For example, underwater robots can explore the depths of the ocean and gather data on marine ecosystems, while aerial drones can fly over forests and other hard-to-reach areas to collect information on vegetation and wildlife.

Robots can also perform tasks that are too repetitive or time-consuming for humans, such as monitoring air and water quality. This can lead to more accurate and timely data collection, which in turn can help us better understand and address environmental issues.

Another way robots can address environmental issues is through their ability to perform precise and targeted actions. For example, robots can be programmed to remove invasive species from a particular area, without harming other plants or animals. They can also be used to clean up pollution in areas where it would be difficult or dangerous for humans to do so.

Finally, robots can be used to optimize agricultural practices, such as precision farming. By using sensors and other technologies to monitor soil conditions, crop growth, and pest populations, farmers can reduce the amount of fertilizer and pesticides they use, leading to less pollution and healthier ecosystems.

Overall, the use of robots in environmental management has enormous potential to help us protect and preserve our planet for future generations.

There is still a need to consider research on long-term autonomy, deploying vehicles at significant depth, and system design to consider, such as what is the optimal system architecture from single units to swarms for agriculture, underwater monitoring and aerial-based surveillance.

3.4. Education

Over the past 25 years, we have seen programs like FIRST, VEX, and Botball provide robotics experiences for K-12 students, typically culminating in a competition. While these programs provide educational experiences, they are not in every school in the US, leading to unequal educational opportunities for children in the U.S. More often than not, robotics programs are extra experiences in after-school programs, which can result in selection bias (i.e., the programs will be less diverse than the school system) and can mean additional costs that some families do not have. Additionally, programs created by individual faculty or universities for individual schools result in a tremendous amount of effort, and efforts that are highly disorganized if one were looking for a new program at their K-12 school.

As a community, we should develop K-12 robotics programs that are easy to find, adapt and use. Programs could be online, or the robotics community could unite to offer common national programs in their regions. While school curriculum is set at the state and local level, coordinated efforts similar to the NSF-funded CS 10K program that led to K-12 CS teachers being trained across the US, as well as the development of the AP CS Principles exam. An AP Robotics exam would expand the number of schools offering robotics.

At the university level, we need to start developing offerings at higher levels as more high school students enter with a robotics background. Just as many K-12 robotics programs have been developed, numerous universities have developed undergraduate robotics courses and curricula. Sharing curricula can have benefits for all, but can be especially beneficial to smaller colleges, minority serving institutions, and community colleges.

While developing educational resources, we should also focus on increasing diversity, equity, inclusion, and accessibility in robotics, AI, and STEM. For example, all funded NSF research requires broader impacts and many NSF awards now require a BPC plan, whether departmental or individual. Exemplars could be shared with the other AI Institutes and with other groups (e.g., Girl Scouts, National Center for Women and IT, Boys & Girls Clubs, Computer Science Teachers of America) for replication. Such efforts at the K-12 level will provide a number of benefits, including increasing the diversity of populations studying these fields at community colleges, at undergraduate institutions, and at universities. These efforts will also lead to a more informed population for students who choose not to pursue further education on these topics.

3.5. Safety and Ethics

As robots become more prevalent in society, there are a number of safety and ethical considerations that need to be addressed to ensure that they are deployed in a responsible and beneficial way. Some of these considerations include:

1. Safety: A primary concern with robots is ensuring that they do not pose a danger to humans. This includes both physical safety, such as preventing robots from causing injury or damage, and cybersecurity, such as protecting against hacking and data breaches. As such, it is important to establish clear safety standards for robots and to ensure that they are properly tested and certified before being deployed in society. Standards exist today for use of robots but often the rules are inconsistent, confusing, and hard to deploy. There is a need for research on deployment and safety across the diverse domains of manufacturing, services, healthcare, transportation, agriculture, etc.
2. Privacy: Robots gather and process large amounts of data about their environment and the people around them. This can raise concerns about privacy, particularly if the data is used for commercial or other purposes without the consent of those involved. To address this, it is important to continue to establish guidelines for data collection, storage, and use, as well as to provide transparency and control over how data is shared.
3. Bias: Robots and artificial intelligence systems can be influenced by bias and stereotypes, which can result in discriminatory outcomes. For example, if a facial recognition system is biased towards certain races or genders, it may lead to false identifications or arrests. To prevent this, it is critical to develop algorithms and systems that are free from bias, and to regularly monitor and test them to ensure that they are fair and equitable.
4. Social impact: As robots become more prevalent in society, they may have a significant impact on jobs and the economy. It is essential to consider the potential social and

economic implications of increased automation, and to develop policies and strategies to mitigate any negative effects.
5. Ethical considerations: There are also a number of broader ethical considerations to take into account when deploying robots in society. For example, there may be questions about the role of robots in decision-making, the appropriate use of force by autonomous systems, and the responsibility of manufacturers and operators for the actions of robots. To address these issues, it is important to engage in ongoing dialogue and debate about the ethical implications of robotics and to develop ethical frameworks and guidelines for their use.

Overall, while robots have the potential to greatly benefit society, it is essential to address these safety and ethical considerations to ensure that they are deployed in a responsible and beneficial way.

3.6. Autonomy and Human-Robot Interaction

The deployment of autonomous robot systems faces multiple challenges, some of the main ones include:

1. Technical limitations: There are still many technical limitations to overcome, particularly in the areas of perception and control. For example, autonomous robots struggle to navigate complex environments, recognize objects, or make decisions in real-time. We are gradually starting to see progress on semantic mapping of the environment to not only have a purely geometric understanding of the environment. It is a challenge in many cases to understand the intent of other agents in the environment, and real-time planning is often a computational challenge.
2. Safety: Safety is a top concern when deploying autonomous robot systems, especially when they are interacting with humans. Ensuring that these systems are safe requires extensive testing and validation, and regulatory agencies may need to develop new safety standards.
3. Legal and regulatory frameworks: There may be legal and regulatory barriers to deploying autonomous robot systems in certain industries or settings. For example, there may be regulations governing the use of autonomous vehicles on public roads, or restrictions on the use of drones in certain airspace.
4. Cost: Autonomous robot systems can be expensive to develop and deploy, which may limit their adoption in some industries or applications.
5. Interoperability: There is a need for standardization and interoperability between different autonomous robot systems, particularly when it comes to communication and data sharing.

Human-robot interaction (HRI) is a critical component of new systems, as it determines how robots interact with and respond to humans in various settings. HRI can take many forms, from simple voice or touch commands to more complex forms of communication and collaboration.

One important use of HRI in autonomous systems is to ensure that robots can operate safely and effectively in human environments. For example, robots may need to navigate crowded public spaces or interact with human coworkers in industrial settings. HRI can help ensure that robots can move and act in ways that are safe and non-disruptive to humans, while also enabling effective communication and collaboration between humans and robots.

Another key use of HRI in autonomous systems is to improve efficiency and productivity. By allowing humans to interact with robots in natural and intuitive ways, HRI can enable robots to perform complex tasks more quickly and accurately, while also reducing the cognitive burden on human operators.

However, there are several challenges associated with HRI in autonomous systems. Some of these include:

1. Limited understanding of human behavior: Robots can not yet fully understand human behavior, which makes it difficult for them to predict and respond to human actions and intentions.
2. Communication barriers: Humans and robots have different modes of communication, and it can be challenging to develop systems that enable effective communication and collaboration between the two.
3. Trust and acceptability: Humans may be hesitant to work with or interact with robots, particularly in situations where robots are responsible for performing critical tasks or making decisions that affect human safety.

Addressing these challenges will require a collaborative effort between industry, government, and academic researchers. It will be important to invest in research and development, develop new regulatory frameworks, and engage with the public to build trust and understanding around autonomous robot systems.

3.7. Artificial Intelligence and Machine Learning

Robots are currently deployed in a wide variety of locations, including hospitals, grocery stores, workplaces, warehouses, manufacturing floors, the sidewalks of college campuses, and on our streets. Some Americans have already found themselves bystanders to such robot systems, with no knowledge of the particular robot and little prior experience with any robots. As robots take on more complex tasks with increased requirements to physically interact with or move in spaces alongside people, can a robot convey how it expects to move and interact to provide safety? Just as standard road signs, brake lights, and turn signals were developed for cars, standards could be created for robots to safely share spaces with us. The development of federal requirements for robot systems, developed with robotics companies, researchers, and the public, would provide clear guidelines for conveying robot intent to others.

Aside from understanding a robot’s current state and movement in the immediate future, encouraging the development of systems that have the ability to explain their actions, whether to bystanders or to regular users of the system, will improve understanding of the robot’s decisions and facilitate trust of the system – and will reduce bias in systems that can explain how they made decisions. Robots with such capabilities could also provide after-action reports, if needed. Achieving these goals will require a mix of requirements for robot systems that operate in the real world, continued research funding to solve open problems in explainability and human-robot interaction, and interdisciplinary collaborations that include social scientists, engineers, computer scientists, and designers.

A key part of robotics is perception, as mentioned above. Another area where AI will play a key role is in decision-making. Many applications have leveraged basic decision-making such as Markov Decision processes (MDP). Using much larger domain datasets, it is possible to build more effective decision engines and also accept more uncertainty in knowledge about the state of the environment. It will be essential to consider AI/ML research that enables more complex domains and leverage the vast amount of data available.

Already today, machine learning enables much improved perception performance due to the ability to train more complex detection and tracking systems. However, we are still far away from truly robust systems that operate under very diverse environmental conditions. Robot systems have to have a reliability of 99.9….% and we are nowhere close. The emphasis should not just be on better numbers, but systems that are grounded in reality.

Recently we have seen major progress on large language models (LLM) and Generative Pre-trained Transformer (GPT) models. They have the potential to revolutionize many aspects of robotics from interaction to semantic models. However, there are a number of research challenges that need to be addressed before we will see wide-spread adoption.

One challenge is that LLMs are not always accurate. They make mistakes, such as generating factually incorrect statements or that are biased.

Another challenge is that LLMs are not always transparent. It is often difficult to understand how an LLM makes decisions. This could make it difficult to trust an LLM's decisions, and it could also make it difficult to hold an LLM accountable for its decisions. Especially for robot safety this would pose a challenge.

Despite these challenges, LLMs have the potential to revolutionize applications areas. As LLMs continue to develop, they will become more accurate, transparent, and fair. This will make them more suitable for use.

Here are some additional research challenges related to LLMs:

- **Bias:** LLMs are trained on large datasets of text and code, which can contain biases. This means that LLMs can generate decisions that are biased, or that reflects the biases of the data they were trained on.
- **Safety:** LLMs are complex systems that can be difficult to understand and control. This means that there is a risk that LLMs could be used to generate harmful or dangerous decisions.

- **Ethics:** LLMs can be used to make decisions that have a significant impact on people's lives. This means that it is important to consider the ethical implications of using LLMs.

LLM has a tremendous potential and there is a significant need for more research. So far, these models are main used for semantic domains and there is a need to study how they can be utilized as part of perception-action systems and long-range planning. As we see more generative models it will also be essential to study new methods for doing verification when the effort switches from generative to analysis to ensure end-system correctness.

4. Implementation considerations

As mentioned in the introduction, there are robotics programs in different agencies, but there is limited coordination across these programs. Other countries/regions such as China, Korea, and Europe have built strong cross agency programs to ensure a holistic policy for investments and research in robotics. The National Robotics Initiative did at the minimum have an interagency coordination group that ensured awareness across agencies.

It is imperative that new initiatives in robotics also consider the scope of national programs. Are all the required components addressed for fundamentals to systems. The present FRR program is focussed on systems' science rather than component technologies. Some agencies such as ONR address autonomy, but there are close to no programs that invest in fundamentals such as grasping, locomotion, grippers, sensors, new materials, etc. The US is quickly falling behind due to a lack of a holistic research vision for robotics and its use-cases.

Doing experimental research in robotics is a challenge, as the resources required to perform such research requires access to physical systems. Even a modest manipulator with basic sensors and grippers is more than $100k. A full scale multi-robot system with motion capture, sensors, etc. is easily $1M and this is in a field where technology changes rapidly. As such, it may not be realistic for every research institution to have full scale experimental facilities. One possible option would be to build a national network of research facilities for robotics, where major research infrastructure is available for the broader community. A few years ago NSF funded the Georgia Tech Robotarium for multi-robot experiments (Wilson et al. 2020). This was both a great example of infrastructure, but also the research needed to make such facilities successful. To ensure the research in robotics is empirically grounded it is proposed to set a limited test of national test facilities across manufacturing, warehousing, home-case, surgery, multi-robot systems, drones, agriculture, and infrastructure which in turn can serve as community centers for test and evaluation.

4.1 Accelerate innovation by facilitating the testing and use of robots in the US

Rapid iteration of designs and testing is critical when developing new technologies. While safety is equally important, we have observed that our country's mix of local, state and federal policies and regulations can prevent robot systems from being piloted and tested in the real world. Even when policies are updated, the time needed to develop and implement such policies can drive innovation from the US to other countries. For example, just a few years ago, Amazon opened operations in the United Kingdom to test their Prime Air UAV in 2016 and Google headed to Australia to test their Wing UAV in 2017. Through the FAA's development of new policies, including Part 135, this work was able to return to the US.

We must also be cognizant of potential biases that could be introduced through these policies. For example, will UAV flight corridors be created that favor flying over less economically advantaged areas, similar to how poorer neighborhoods were demolished when the Interstate Highway System was built? Will some robots be deployed primarily in more affluent areas, creating greater economic disparities, as we have seen with some AI-based systems in the past? Efforts are required to lead to the development of guidelines that industry and communities can use for fast, safe, and equitable development of technology.

4.2 Moving from research to market

AI and robot systems that can assist people in living longer, healthier, and more independent lives are often the subject of federally funded research. For example, AI and robotics systems in the home can provide assistance with activities of daily life for people with motor and/or cognitive challenges. In the military and on manufacturing floors, exoskeletons can reduce the impact of physical tasks on people's bodies. Other robot systems are being developed to assist people with Autism Spectrum Disorder.

However, despite the federal resources devoted to these important problems, few of the developed systems have made it to market. A cross-agency effort to determine the root causes (e.g., failure to move from basic research to large-scale user studies, FDA approvals, lack of funding for purchases from public and private insurers) would facilitate the necessary changes to allow such systems to benefit Americans.

In general, there are programs such as iCorps, STTR, and SBIR to assist with the translation of technology. It would be of value to try to build more targeted programs that leverage the agency programs, integrate them with access to VC companies, and experienced founders to build a successful program for tech transfer. There is an opportunity for NSF's new TIP Directorate to play a role in developing such cross-agency programs.

5. Recommendations

The United States has a history of inventing new technologies and subsequently seeing the successful commercialization of these technologies elsewhere. The automotive industry is a great example, so are windmills and industrial robotics to mention a few others. There is a need to sustain R&D, build strong companies, and have a holistic view of how we can build societal ecosystems for continued innovation, economic growth, and effective utilization.

To gain/maintain leadership in robotics, there is a need for:

1. Increased funding for robotics within a multi-agency framework. It is not realistic for a single agency (NSF) or single unit (CISE / ENG) to address all the challenges. The program should address both fundamental research, component technologies, systems integration, ethical and legal considerations. A reductionist approach is not an optimal strategy for continued leadership in robotics.
2. Interagency coordination to optimize the limited resources available from different agencies.
3. Investments in robotics infrastructure. Trying to build strong experimental facilities at most universities is not cost-effective and unlikely to generate sustainable facilities.
4. Leverage / expand programs to transition research into technologies that can be commercialized by new or existing companies to ensure that the next-generation robotics industry is being built in the United States.
5. Ensure we have effective legal frameworks for production and adoption of these technologies.
6. Education of a diverse group of next-generation leaders and entrepreneurs that can drive the innovation and adoption of robot technology.

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