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A Roadmap for US Robotics

Robotics for a Better Tomorrow

2024 Edition

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Executive Summary

Theme: Robotics for a Better Tomorrow

The field of robotics was established 70 years ago. Early industrial successes were also first seen in the USA and yet today, the USA is no longer the leader in robotics. When the first national robotics roadmap was published in 2009 USA was considered 4th in adoption of robotics for industrial applications such as automotive, aerospace and appliances. It was leading in the world of home robots and logistics. Today, 15 years later, the US is 10th worldwide in adoption of robotics and the Asian market is 5-10 times bigger than the US market. Last year, China purchased 52% of all robots sold. It is no longer evident that robotics is a national priority in the USA.

The field of robotics is at an inflection point. Component technologies such as materials, embedded systems, and artificial intelligence are seeing exponential growth, which in turn catalyze major progress in robotics. The field is rapidly changing, both in terms of science progress and new applications. Robotics will impact most aspects of our daily lives in the near future, from our homes over work to leisure activities. Already today 82% of the population lives in urban environments, and this is expected to increase to 90% before mid-century. This will challenge infrastructure, logistics, construction, and security. All the aspects of manufacturing, services, home activities and leisure will benefit from the use of automation and robotics.

The societal megatrends are also pointing to a clear need for increased utilization of robot technology. There is a need to reshore manufacturing from cars to semiconductors. There is at present (post-COVID) a workforce shortage. According to the Federal Reserves, there are only seven workers available for every ten open industry jobs[1]. Without "tools" to increase productivity, economic growth will be challenged. The population is aging 8 hours / day, which over time results in a reduced workforce and a significant increase in the number of people above 65, which will challenge the healthcare system and those desiring to remain in their homes for extended periods of time to continue to have a quality of life. In a world of rapidly changing technology there is also a need to provide the mechanisms for continued workforce training to retain and develop good conditions for economic growth.

During the last four years, the National Robotics Initiative was sunset[2] and the Congressional Caucus on Robotics was not active (last activity May 2019). National agencies have by now largely uncoordinated smaller investments in robotics. These indicators point to the fact that robotics is no longer a US national priority, creating a risk of long-term challenges for US competitiveness.

Recommendations:

- Robotics technology will transform society and is likely to become as ubiquitous within the next decade as computing technology is today. As it stands, this development will not occur in the US. As such, robotics ought to be a national government priority (again)

[1] https://www.bls.gov/news.release/jolts.nr0.htm
[2] https://www.nsf.gov/pubs/2022/nsf22081/nsf22081.jsp

- There should be cross-agency coordination for R&D, innovation and utilization of robot technology. The need for a holistic vision across industry, academic and government is critical to the nation
- The Congressional Robotics Caucus should be reinvigorated to ensure appropriate prioritization at all levels
- There is a need to unify funding programs across agencies to make it easier for researchers, developers, and entrepreneurs to access these opportunities
- There is a need to consider mechanisms to support the US industry to be competitive across regions and nations
- Increased attention is needed on workforce training to address the shortage and to ensure adaptation to new technology

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PREFACE

Robotics affects many aspects of society - industry, education, science, and defense, etc. consequently, a roadmap requires a fusion of ideas from a diverse community. As such, this is a collaborative project that involves a diverse set of members from the community, including researchers and industry leaders, who have contributed white papers with innovative ideas for the next roadmap. We are deeply grateful for their contributions and fortunate to have a dedicated and committed community, without whom this update would not have been possible.

We would also like to express our gratitude for the financial support provided by the Computing Community Consortium (CCC) and the Engineering Research Visioning Alliance (ERVA). Additionally, we are thankful for the support from the organizing institutions - UC San Diego, University of Pennsylvania, University of Texas Austin, and Arizona State University.

Special recognition goes to the synthesis team, consisting of Joydeep Biswas from UT Austin, Martin Buehler from J&J, Todd Danko from GE Vernova, Maria Gini from UMN, Pramod Khargonekar from UC Irvine, Maja Mataric from USC, Allison Okamura from Stanford, Nikos Papanikolopoulos from UMN, Bill Smart from OSU, Mike Tolley from UCSD, Holly Yanco from UML, and Wenlong Zhang from ASU. They were assisted by graduate students from UCSD who served as Roadmap Assistants: Iman Adibnazari, Pratyusha Ghosh, Sandhya Jayaraman, Dongting Li, Will Sharpless, and Henry Zhang. Thank you for spending a weekend locked up in San Diego. The support from the synthesis team and assistants was invaluable in finalizing the document.

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1. Introduction

Given the progress in science and technology and major changes in the workforce, it is timely to update the National Robotics Roadmap. The world is changing rapidly due to technology developments, new opportunities, and challenges. In particular, technologies such as material, computing and artificial intelligence have progressed significantly over the last four years. Robotics has the potential to play a big role in many different domains. The confluence of AI, material and computing radically changes the field of robotics.

Major progress has been achieved in material science to build soft robot mechanisms that can be sensorized to generate much more effective methods for physical interaction with the world from small-scale handling of medical samples or pharma development to construction of mega-structures such as bridges, offshore windmills or effective manufacturing of one-off products.

Computer systems have also seen significant progress on processing power, both for embedded systems and for datacenters. Today, processing petabytes of data is easily within reach. Processing large scale data at the edge / in embedded systems is achievable with dedicated processors for real-time problems.

Artificial Intelligence has seen major progress with foundational models, new methods for processing data, methods for effective machine learning, and methods for certifiable use of AI, not to mention effective methods for utilization of language models be it for human interaction, for processing of medical data or generating new methods for entertainment.

In parallel, the nature of work has changed post-COVID. For manufacturing and logistics, the number of people in the workforce was close to the number of open positions before 2020. This is no longer the case. Today (2024) there are only seven people in the workforce for every ten open positions. In many respects, the workforce has changed with more remote work and new types of work modalities. In addition, the demographic is changing with more people retiring, while birthrates remain low.

The roadmap has been updated every four years since it was first published in 2009. The initial roadmap resulted in the National Robotics Initiative, a cross agency program to promote R&D in robotics. The initial program engaged NSF, USDA, NIH and NASA with an annual budget of $100M+. Every iteration has had a theme. For 2009 it was the productivity reboot after the economic downturn. The 2013 version was about expansion beyond the factory floor and the broader impact, motivated by the societal impact x3from the earthquake in Japan. In 2016, reshoring was already a major consideration. For 2020, an obvious theme was societal and economic growth in a post-COVID era. For 2024, key considerations are related to the utilization of the advances in artificial intelligence, how to address the workforce shortage, and a more explicit emphasis on sustainability.

1.1. The roadmapping process

The roadmapping process was initiated in collaboration with the Computing Community Consortium (CCC) and the Engineering Research Visioning Alliance (ERVA), and we appreciate their support.

A call for two-page white papers was issued in June 2023. Based on roughly 60 white papers and another 60 white papers published in a related process, participants were invited to one of three workshops. The workshops took place in September 2023 at the University of Pennsylvania, in November 2023 at the University of Texas Austin, and in December 2023 at Arizona State University. A good mixture of representatives from industry and academia were present at the meetings. Written statements were recorded and made available on a shared cloud drive to all participants. All the collected information - white papers, background research, and workshop summaries provided the basis for a synthesis workshop that took place at UC San Diego in March 2024. There, the organizers of the roadmap gathered and generated the key sections of the roadmap, which were subsequently edited into a unified document.

1.2. Outline of the rest of the report

Initially, major megatrends that are shaping society in general terms over the next decade are covered. These megatrends are key factors that will impact the future independently of progress in robotics but serve as a core basis for the future. In Chapter three, the main business drivers for the future use of robotics technology are outlined. The chapter covers a diverse set of verticals from manufacturing to healthcare and leisure. The chapter outlines the main drivers for economic growth and industrial opportunities. While the drivers are presented in chapter three, the challenges to delivering solutions are covered in chapter four. The challenges come in many varieties from progress on materials, access to data, new computing, user interfaces, etc. These challenges in turn point to a need for further R&D. The main issues to be addressed for continued growth are presented in chapter five. The issues to be addressed. This in turn points to the initiatives that have to be undertaken to ensure that the United States is one of the leaders in robotics.

1.3. Main recommendations

- During the past four years, the National Robotics Initiative (NRI) was discontinued[3]. Originally created in 2011 as a multi-agency R&D initiative, NRI involved NSF, USDA, NIH, and NASA, and over time, also included NIST and other federal agencies. There is a need for a program such as the NRI, which is supported by multiple agencies and has a single portal for applications across agencies. NRI has been proven to be more effective because it made the process more efficient.. In the standard funding model, too often applications are rejected on the grounds of poor fit to a particular program or agency, resulting in inefficiencies in innovation. The US cannot afford not to be the innovation leader..

[3] https://www.nsf.gov/pubs/2022/nsf22081/nsf22081.jsp

- The socio-economic-technological ecosystem that connects research and development to real-world, practical implementation at-scale is dynamic, complex, and interconnected. Federal investments in research and development will have maximal societal benefits only if this ecosystem is fully considered from the very beginning.
  Insights from real-world implementations need to be rapidly brought back to the research and development programs to minimize waste and maximize successes. We recommend the creation of an inter-agency working group that includes representatives from federal agencies that are responsible for economic competitiveness (DoC, DoT, FAA), health (HHS), and security (DoD, DoE) and representatives from key R&D agencies (NSF, DoE, DoD, NIST). This working group would be charged with the responsibility of ensuring that the design and implementation of research programs is tightly connected with the development and demonstration programs. This working group should convene program managers and performers from academic, industry, and government sectors to increase communication and linkages throughout the ecosystem. The working group should connect with other inter-agency working groups, e.g., AI, NITRD, to ensure coordination and reduce duplication of efforts.

- During the last roadmap period (2020-2024), the Congressional Caucus on Robotics was retired (no activities since May 2019). It is recommended that the Caucus is re-activated. It is essential for robotics to be a national priority due to all the societal benefits outlined in this report. Today there is a Congressional Caucus on Artificial Intelligence, which is commendable. However, many key parts of robotics, such as the mechanical design, soft robotics, and control, are not directly covered by the AI Caucus and other committees. The physical interaction with the world is central to robotics, and it differentiates it from AI, while also making it a complement to modern AI.

- There is also a need to consider how industry can be supported in the development, adoption and use of robotics technology. This should be through a program such as the National Manufacturing Institutes, SBIR programs, etc. but there should also be more targeted programs.

- Finally, training and reskilling of the workforce is essential. Already today there is a significant shortage in the workforce and as the demographics evolve, this will become much more of a priority. Without an adequate and trained workforce, quality of life and economic growth will be challenged. There is a need to invest in training and education across trade-schools, colleges and continuing education programs.

2. Megatrends

Megatrends are major, transformative global forces that define the future and have a widespread impact on businesses, economies, industries, societies, and individuals. Some characteristics of megatrends include

1. Scale and Scope:
   - Megatrends are large-scale, long-term shifts that affect a wide range of activities, processes, and perceptions across the globe.
   - They have the potential to transform the economic, social, political, environmental, and technological landscape.
2. Pervasiveness:
   - Megatrends cut across multiple sectors, industries and domains.
   - They influence and shape the development of other trends, creating interconnected and cascading effects.
3. Longevity:
   - Megatrends typically unfold over decades, with their impacts felt for an extended period.
   - They are distinct from short-term trends or fads that come and go more quickly.
4. Inevitability:
   - Megatrends are considered largely inevitable, given the scale and momentum behind their drivers.
   - While the specific manifestations may vary, the overall trajectory and direction of megatrends is difficult to reverse or stop.

We include megatrends in the roadmap as indicators of major changes that are expected to impact the US. These predicted changes need to be an integral part of a roadmap for the next 10–15 years.

2.1. Robotics as an embodiment of AI

Some of the major megatrends in AI and robotics that are expected to have a significant impact on the United States over the next decade:

1. Continued Advancements in Machine Learning and Deep Learning:

   - Rapid progress in areas like computer vision, natural language processing, and reinforcement learning.

   - Widespread adoption of deep learning techniques for tasks like image classification, language understanding, and decision-making.

   - Increasing ability to tackle more complex, real-world problems with AI.

2. Growth of Artificial General Intelligence (AGI) Research:
    - Ongoing efforts to develop AI systems with more general, human-like intelligence.
    - Potential breakthroughs in areas like reasoning, common sense understanding, and transfer learning.
    - Debates around the implications and risks of advanced AGI systems.
3. Pervasive Automation and Robotics:
    - Rapid advancements in robotic technologies, including improved sensors, dexterity, and autonomy.
    - Increased deployment of robots in industries like manufacturing, logistics, healthcare, and service sectors.
    - Concerns around the impact of automation on job displacement and the need for workforce retraining.
4. Convergence of AI and Robotics:
    - Integrating AI-powered decision-making and control systems into robotic platforms.
    - Emergence of more intelligent, adaptive, and collaborative robots that can work alongside humans.
    - Potential for AI-powered robots to take on a wider range of tasks and roles in society.
5. AI-Powered Personalization and Customization:
    - Widespread use of AI for personalized recommendations, content curation, and targeted marketing.
    - Increased demand for AI-driven personalization in consumer products, services, and experiences.
    - Privacy concerns and debates around the ethical use of personal data for AI-powered personalization.
6. AI Ethics and Governance:
    - Growing focus on developing ethical frameworks, guidelines, and regulations for the responsible development and deployment of AI.
    - Efforts to address issues like algorithmic bias, privacy, transparency, and accountability in AI systems.

    - Increased collaboration between policymakers, industry, and the public to shape the future of AI governance.

7. AI-Driven Scientific Discovery and Innovation:
    - Utilizing AI techniques, such as machine learning and simulation, to accelerate scientific research and innovation.
    - Potential breakthroughs in fields like drug discovery, materials science, and renewable energy.
    - Challenges around the interpretability and validation of AI-driven scientific insights.

These megatrends in AI and robotics are expected to have far-reaching implications for the US economy, workforce, national security, and society as a whole. Adapting to these changes and ensuring the responsible development and deployment of these technologies will be crucial for the United States in the coming decade.

2.2. Workforce

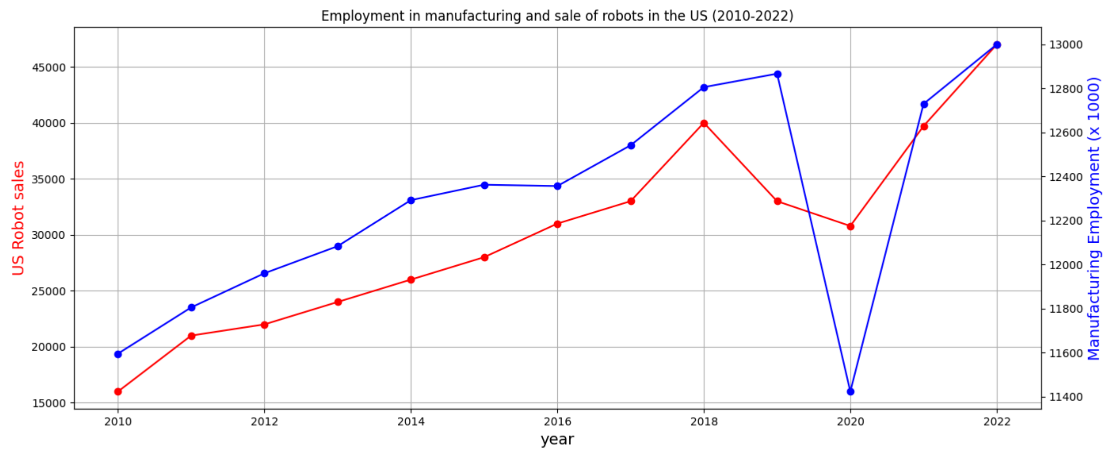
Changes in the workforce due to advancements in AI and robotics are expected to have a significant impact on the United States over the next decade. Here are some of the key ways these changes could affect the country:

1. Job Displacement and Skill Shifts:
    a. Increased automation of routine and manual tasks in industries like manufacturing, transportation, and customer service.
    b. Displacement of workers in these sectors, leading to job losses and the need for workforce retraining.
    c. Increased demand for workers with skills in areas like data analysis, digital technology, and creative problem-solving.
2. Widening Skills Gap and Talent Shortages:
    a. Mismatch between the skills required for new, technology-driven jobs and the skills possessed by the current workforce.
    b. Challenges in reskilling and upskilling workers to keep pace with the changing job market.
    c. Competition for talent in emerging fields like AI, robotics, and data science.
3. Changing Workforce Dynamics and Work Arrangements:

   a. Growth of the gig economy, with more flexible and on-demand work arrangements.
   b. Increased remote work and distributed teams enabled by AI and digital collaboration tools.
   c. Challenges in maintaining work-life balance and employee well-being in the face of these changes.
4. Demand for Lifelong Learning and Continuous Upskilling:
   a. Necessity for workers to continuously acquire new skills and adapt to technological changes.
   b. Increased emphasis on education and training programs that support ongoing skill development.
   c. Collaboration between employers, educational institutions, and policymakers to address evolving skill needs.
5. Shifts in Industry Composition and Employment Patterns:
   a. Decline of traditional industries and the emergence of new, technology-driven sectors.
   b. Geographic shifts in employment, with some regions and communities experiencing more significant disruption than others.
   c. Potential for increased income inequality and regional economic disparities if the benefits of technological change are not equitably distributed.
6. Regulatory and Policy Challenges:
   a. The need for policymakers to address issues like worker protection, social safety nets, and fair compensation in the face of widespread automation.
   b. Debates around the role of government in supporting workforce reskilling, job transition programs, and the development of new industries.
   c. Potential for political tensions and social unrest if the impacts of technological change are not effectively managed.

To mitigate the potential negative consequences and harness the benefits of these workforce changes, the United States will need to invest in education, training, and upskilling programs, as well as develop policies and regulations that promote inclusive economic growth and worker well-being in the face of technological disruption

Over the last 10 years we have seen a significant increase in employment in manufacturing and correspondingly in utilization of robot systems. Economic growth is achieved through joint utilization of automation and hiring of more people.



It is evident that economic growth is achieved through both automation and hiring. The data are from the International Federation of Robotics[4] and the Bureau of Labor Statistics[5].

2.3. Digital Economy

The growth of the digital economy is expected to have a significant impact on US society over the next decade. Here are some of the key ways this is likely to play out:

1. Shifts in Employment and Income Patterns:

    a. Increasing automation and digitization leading to job displacement, particularly in routine and manual tasks.

    b. Growth of the gig economy and freelance/contract work, challenging traditional employment models.

    c. Widening income inequality as highly skilled, tech-savvy workers benefit more than those without digital skills.

2. Transformation of Consumption and Retail:

    a. Rapid expansion of e-commerce and online shopping, disrupting traditional brick-and-mortar retail.

    b. Increased personalization and targeted marketing enabled by AI and data analytics.

[4] https://ifr.org/free-downloads/

[5] https://data.bls.gov/timeseries/CES3000000001

    c. Challenges for physical retail spaces and communities heavily dependent on traditional retail.

3. Changes in Education and Workforce Development:

    a. Increased demand for digital skills and STEM-focused education.

    b. Growth of online and distance learning, blurring the lines between physical and virtual education.

    c. Need for continuous reskilling and upskilling to keep pace with technological change.

4. Impacts on Healthcare and Social Services:

    a. Adoption of telemedicine, remote patient monitoring, and AI-powered diagnostic tools.

    b. Improved access to healthcare in underserved areas, but potential widening of digital divides.

    c. Challenges in ensuring data privacy and security in the digital healthcare ecosystem.

5. Transformation of Entertainment and Media:

    a. Shift towards streaming, on-demand, and personalized entertainment content.

    b. Increased integration of digital technologies, such as VR and AR, in entertainment experiences.

    c. Disruption of traditional media business models and the rise of new digital platforms.

6. Evolving Social Interactions and Community Engagement:

    a. Increased reliance on social media and online platforms for communication and social interaction.

    b. Potential for digital technologies to both enhance and isolate social connections.

    c. Concerns about the impact of social media on mental health, particularly for younger generations.

7. Cybersecurity and Data Privacy Challenges:

    a. Growing threats of cyberattacks, data breaches, and identity theft as more aspects of life move online.

    b. Debates around balancing user privacy and the benefits of data-driven personalization and services.

    c. Need for robust cybersecurity measures and data governance frameworks to protect individuals and society.

2.4. Changing Demographics

The United States is expected to see significant demographic changes over the next decades[6], and these shifts will likely profoundly impact both our society and economy.

1. Aging Population:
    - Continued aging of the baby boomer generation, with the 65+ population projected to grow from 16% in 2020 to 22% by 2040.
    - Increased demand for healthcare, social services, and retirement/pension systems to support the growing elderly population.
    - Potential labor shortages as the working-age population shrinks relative to retirees, putting pressure on economic productivity.
2. Increasing Racial and Ethnic Diversity:
    - Continued growth of racial and ethnic minority populations, including Hispanic, Asian, and Black Americans.
    - Shifts in cultural norms, values, and consumer preferences as the population becomes more diverse.
    - Potential challenges in ensuring equitable access to education, employment, and other opportunities for all demographic groups.
3. Geographic Shifts in Population:
    - Migration patterns, such as the continued movement of people from the Midwest and Northeast to the South and West.
    - Growth of urban and suburban areas, with potential strain on infrastructure and public services in these regions.
    - Challenges for rural and Rust Belt communities experiencing population decline and economic stagnation.
4. Changes in Household Composition:
    - Decline in traditional nuclear family structures, with more single-person and non-family households.

[6] https://www.usa.gov/census-data

    - Increase in multigenerational households as younger adults live with parents or grandparents.
    - Evolving family dynamics and support systems, potentially impacting social services and caretaking responsibilities.
5. Declining Birth Rates and Fertility:
    - Continued low fertility rates, leading to a slower-growing or even declining native-born population.
    - Potential labor shortages and challenges in sustaining economic growth and social programs.
    - Debates around the role of immigration in addressing population and workforce challenges.

These demographic shifts will have far-reaching implications for the United States, including

Economic Impacts:

- Changes in consumer demand and spending patterns
- Workforce and labor market dynamics
- Strains on social safety nets and government budgets

Social Impacts:

- Evolving community structures and social support systems
- Changing cultural norms and values
- Challenges in ensuring social cohesion and integration

Policy Challenges:

- Adapting education, healthcare, and social services to meet the needs of a changing population
- Addressing regional disparities and inequities
- Developing immigration policies that balance economic needs and social concerns

Navigating these demographic changes will require a multifaceted approach, involving collaboration between policymakers, businesses, communities, and citizens to ensure the United States remains economically vibrant and socially cohesive in the decades ahead.

2.5. UN Sustainability Goals

The United Nations Sustainable Development Goals (UN SDGs)[7] are a set of 17 interconnected global goals aimed at addressing key challenges facing the world, including poverty, inequality, climate change, and environmental degradation. While the SDGs are global in scope, their implementation and impact on US society over the next two decades are likely to be significant. Here are some potential predictions:

1. Environmental and Climate Action:
    - Increased focus on renewable energy, energy efficiency, and sustainable infrastructure to support the transition to a low-carbon economy.
    - Stricter regulations and incentives to reduce greenhouse gas emissions, improve air and water quality, and protect natural ecosystems.
    - Shifts in consumer behavior and preferences towards more sustainable products and services.
2. Poverty Reduction and Social Equity:
    - Efforts to address income inequality, improve access to quality education and healthcare, and support vulnerable populations.
    - Increased investment in affordable housing, job training programs, and social safety nets.
    - Potential impacts on tax policies, wealth redistribution, and the social welfare system.
3. Sustainable Consumption and Production:
    - Promote the circular economy, emphasizing reducing waste, reusing materials, and promoting sustainable manufacturing practices.
    - Changes in packaging, supply chains, and consumer attitudes towards more environmentally friendly products.
    - Potential disruption of traditional industries and the emergence of new, sustainable businesses.
4. Sustainable Cities and Communities:
    - Investments in smart, resilient, and livable urban infrastructure, including public transportation, green spaces, and renewable energy systems.
    - Efforts to address urban sprawl, improve access to affordable housing, and enhance community well-being.

[7] https://sdgs.un.org/goals

    - Potential shifts in urban planning, real estate development, and local policymaking.
5. Responsible Consumption and Production:
    - Increased corporate social responsibility and transparency around environmental and social impacts.
    - Shifts in consumer preferences and demand for sustainable, ethical, and traceable products.
    - Potential impacts on supply chains, marketing, and business models across various industries.
6. Partnerships and Collaboration:
    - Strengthened cooperation between the government, private sector, and civil society to drive sustainable development.
    - Increased public-private partnerships and multi-stakeholder initiatives to tackle complex, cross-cutting challenges.
    - Potential impacts on policy making, funding mechanisms, and the role of different actors in achieving the SDGs.

Implementing the UN Sustainable Development Goals in the United States over the next two decades is likely to have far-reaching impacts on the country's economy, environment, social systems, and overall societal well-being. Successful achievement of the SDGs will require a concerted and coordinated effort across all levels of government, the private sector, and civil society.

2.6. The World Is No Longer Flat

The statement that "the world is no longer flat" reflects a shift from the early 21st-century perspective popularized by Thomas Friedman in his book "The World Is Flat,[8]" which highlighted the globalization of markets, outsourcing, and supply chains. Recent developments, however, suggest a reevaluation of the extent to which manufacturing and production are globalized. Several key factors influence this change:

- **Reshoring and Nearshoring Initiatives** - Companies are increasingly bringing manufacturing back to their home countries (reshoring) or moving it to nearby countries (nearshoring) to reduce lead times, minimize supply chain disruptions, and respond more rapidly to market demands. This shift is driven by the need for greater control over production and a desire to mitigate the risks associated with long, complex supply chains.
- **Trade Tensions and Protectionism** - Rising trade tensions and the adoption of protectionist policies by some countries have made global manufacturing more challenging. Tariffs and trade

[8] https://www.thomaslfriedman.com/the-world-is-flat-3-0/

barriers can increase the cost of importing raw materials and exporting finished goods, making it less economically viable for companies to manufacture abroad.

- **Supply Chain Vulnerabilities** - The COVID-19 pandemic exposed the vulnerabilities of global supply chains, demonstrating how disruptions in one part of the world can have cascading effects on production and logistics worldwide. This has led to a reassessment of the risks associated with heavy reliance on global manufacturing networks.
- **Technological Advancements** - Advances in manufacturing technologies, such as automation, 3D printing, and artificial intelligence, have made it more feasible for companies to produce goods closer to their consumer bases. These technologies can offset higher labor costs in developed countries and make local manufacturing more competitive.
- **Sustainability and Environmental Concerns** - There is a growing emphasis on sustainability and reducing the carbon footprint of production and logistics. Localizing manufacturing can lead to shorter supply chains, which reduces transportation emissions and allows for better control over the environmental impact of the production process.
- **Consumer Preferences** - The demand for customized products and faster delivery times is rising. Manufacturing closer to end consumers can help companies meet these expectations more effectively, enhancing customer satisfaction and loyalty.

Future Outlook

The movement towards more localized or regional manufacturing does not mean that global trade and international cooperation in production will disappear. Instead, it suggests a more nuanced approach to manufacturing and supply chain management, where decisions are made based on a broader set of factors including cost, risk, speed, and sustainability. Companies may adopt a more diversified strategy, maintaining a presence in key global markets while also investing in local production capabilities to serve specific regions more effectively. This trend towards "glocalization" – thinking globally but acting locally – reflects a more complex, multidimensional view of how manufacturing and supply chains can be optimized in the 21st century.

3. Opportunities

In many respects, the future opportunities of use of technology is driven by the opportunities to address economic opportunities and/pr to address societal challenges. We will discuss opportunities across manufacturing, logistics, demographics, construction, sustainability and space to make out some of the key drivers.

3.1. Reshoring manufacturing

Manufacturing adds $2.85 trillion to the U.S. economy, accounting for 10.3% of the U.S. GDP[9]. For every $1 spent on manufacturing, there is a total impact of $2.69 on the overall economy. The manufacturing industry employs 13 million people, and there were 601K manufacturing job openings to be filled as of December 2023[10]. With the retirement of experienced workers from Baby Boomers and a lack of skilled workers in younger generations, the U.S. manufacturing labor shortage becomes more concerning and presents major risks to the continued growth of the U.S. economy. Out of 300 Member Respondents to the US National Association of Manufacturing in Q4 of 2023, 71% chose “the inability to attract and retain employees” as their top primary challenge[11].

The COVID-19 pandemic revealed the vulnerability of the U.S. supply chain, given its high dependence on foreign offshore suppliers. For example, 88% of semiconductor production occurs overseas[12]. After the COVID-19 pandemic began, manufacturing output fell at a 43% annual rate and hours worked fell at a 38% rate in the second quarter of 2020[13]. These were the largest declines since World War II. No major industry was immune to the second-quarter declines. The combination of low availability of imported components, high shipping costs, and lack of domestic manufacturing capability caused major disruptions in supplies of motor vehicles, consumer electronics, food and beverages, and chemicals, to name a few.

Robotics presents great promises in redefining future manufacturing, alleviating the labor shortage, and improving the resilience of the U.S. supply chain, as they can improve productivity, reduce cost and error rates, provide labor and utilization stability, and increase access to difficult or dangerous locations. New installations of industrial robots in the United States were up by 14% to 34,987 units in 2021. This exceeded the pre-pandemic level of 33,378 units in 2019 but was still considerably lower than the peak level of 40,373 units in 2018. Moreover, the robot density in the U.S. was 285 robots per 10,000 employees, ranking tenth in the world behind Singapore, Germany, the Republic of Korea, Japan, and China[14]. China employed 392 robots per 10,000 employees, with 38 million people employed in the

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[9] https://www.statista.com/statistics/248004/percentage-added-to-the-us-gdp-by-industry/
[10] https://www.bls.gov/news.release/jolts.t01.htm
[11] https://themanufacturinginstitute.org/wp-content/uploads/2024/04/Digital_Skills_Report_April_2024.pdf
[12] https://www.csis.org/analysis/strategy-united-states-regain-its-position-semiconductor-manufacturing
[13] https://www.bls.gov/opub/ted/2022/u-s-manufacturing-output-hours-worked-and-productivity-recover-from-covid-19.htm
[14] https://ifr.org/ifr-press-releases/news/global-robotics-race-korea-singapore-and-germany-in-the-lead

manufacturing industry. Moreover, the share of companies that use robots is still rather small, especially among small and midsize enterprises (SMEs).

In addition to increased and distributed deployment, there is a need to improve the adaptability and reconfigurability of manufacturing robots. For example, soft and compliant graspers are needed to handle fragile and irregular materials such as in food processing, and specialized end effectors are required to operate in landfills and process bio-waste in hospitals. In semiconductor manufacturing, there are still open challenges for robots to pick and place thin films and substrates without contamination reliably. With an increased demand for customized products, future robots must be highly reconfigurable to manufacture different products on demand.

Human workers and robots coexist in manufacturing facilities, and collaborative robots (co-bots) have received significant attention over the past decade. Safety needs to be addressed such that humans are willing to work next to robots and future factories can be made more compact and energy efficient. A step beyond safety is to enable human-robot collaboration in manufacturing, which has been a popular research topic, but it has not obtained industry-wide acceptance. There is a need to develop approaches to understand the human workers' intentions and plan the robot's collaborative actions accordingly. On a higher level, the robots need to be included in the planning of the entire factory for dynamically assigning tasks to humans and robots, such that the overall manufacturing efficiency and quality of products can be improved while keeping the costs low.

Robots can also play a key role in manufacturing in extreme environments where manual manufacturing is challenging, such as space, underwater, or under extreme weather conditions. These environments pose new challenges for autonomous manufacturing robots, such as precision control, perception and localization, self-diagnostics and self-monitoring, and non-destructive testing of the manufacturing products for quality control.

The U.S. federal government has invested in robotics for manufacturing. The ARM (Advanced Robotics for Manufacturing) Institute[15] was a Manufacturing Innovation Institute (MII) established in 2017 by the Department of Defense with the aim to boost technology and workforce development in this area. It has over 400 members across industry, academia, and government labs as of March 2024. However, the ARM Institute focuses on higher-level TRL projects with possible defense applications, and there is a gap at the federal level to fund early-stage R&D projects in robotics and automation for manufacturing to address many fundamental and important problems for long-term worker wellness and economic competitiveness.

3.2. The "now" economy

The "now" economy involves deploying goods and services as close to the end customer as possible so that they are available nearly instantly upon a customer's demand. This can be accomplished through information-sharing technologies that allow for coordinating local goods and services in near-real time,

[15] https://arminstitute.org/

such as Uber for ride-sharing, or it can be accomplished by anticipating needs and pre-positioning goods and service providers where they are expected to provide the most value.

In an ideal world, any goods or services that could be requested would be immediately (at least before the missing item causes a problem for the consumer) available, however, this is limited by a scarcity of resources (skilled labor and materials). Over-provisioning is not economically feasible, but we can use robotics to make under-provisioned resources into what the end user needs. Robotics can serve to increase the versatility of available resources, whether that is the customization (or fabrication) of goods or the performance of services.

Variations in demand are often difficult to reconcile with the variations in supply. Robotic solutions can be deployed to smooth out both these variations and the challenges associated with the mismatch between supply and demand.

Opportunities for robotic technologies in the “now” economy may include:

- last-mile delivery of goods
- remote delivery of services (teleoperation by experts)
- on-demand automated workforce to make up for shortcomings in the human workforce (fruit picking)

To illustrate the roles robotic systems may serve in the future, imagine:

1. You are on vacation but a pipe bursts in your house. You have a robot that detects this and immediately identifies the nearest upstream valve to the leaking pipe and turns it off. Once the leak has been stopped, the owner is alerted and a technician is called to perform the necessary repairs.
2. You are flying for an important business trip. During your connecting flight’s last leg, a diagnostic process revealed that a critical component must be replaced before it is cleared for takeoff again. This diagnostic check triggers the automatic delivery of the necessary parts to your connecting airport, where a robotic system works shoulder-to-shoulder with airline technicians to perform the necessary maintenance and allow your flight to proceed on time.

Future robotics technologies may be developed that allow consumers to obtain products and services previously slowed by manufacturing time quickly, skilled labor availability or transportation from centralized manufacturing and distribution facilities.

3.3. Feeding the world

Food represents about 12.9% of the average household expenditure in the US and accounts for close to 6% of the GDP or $1.053 trillion (2019)[16]. Food and agriculture also represent about 11% of the

[16] https://www.ers.usda.gov/data-products/ag-and-food-statistics-charting-the-essentials/

employment in the US. More than 9 billion chickens, 241 million turkeys, 131 million hogs, and 33 million cattle and calves were processed during 2018. That is 317 animals processed per second. Meat, wine, and dairy are the three major sectors of the domain in terms of employment. In comparison, the fishing industry is the smallest sector. In particular, the fruit and vegetable industry strongly relies on a migrant workforce.

Climate change has an increasingly significant impact on our ability to feed the world. It increases the frequency and severity of fires, storms, and droughts. As a result, water management is becoming more complex while farmers deal with rising precipitation variability, and varying planting windows, and may have a significant impact on reduced lower crop yields. This will affect our ability to produce food, fiber, and fuel, whose demand is globally increasing due to the growth of population. It should be noted that US global competitiveness and food security are at risk due to rising greenhouse gas (GHG) concentrations, resulting in climate change and degrading health of the agriculture-forest system, and an aging and skill-deficit workforce.

Over the last couple of decades, there has been a growing interest in using robots as part of food processing. The spectrum covers all aspects of food processing, from planting seeds in the ground to weed removal and picking mature fruit/vegetables. More than ten years ago, John Deere presented the concept of a driverless harvester/tractor. The idea was to enable farmers to task a vehicle to maintain crops without requiring a driver to be inside the vehicle, mainly supervising a largely autonomous operation. So far, these vehicles have seen little real deployment. Robots have generally been applied to precision agriculture, weed control, nursery automation, and harvesting. Precision agriculture is used to monitor crops, collect data, and apply fertilizer.

Weed control is either mechanical weeding or delivering small amounts of herbicides for weeks. Nursery automation includes managing weed, transportation, and monitoring. Drones are increasingly used to map out orchards to monitor the state of growth. As such, a modest amount of automation has so far been introduced for use in the field. There is a significant potential for automation in the field, especially in a time when a migrant workforce is harder to get by.

It may be surprising to some but one of the largest areas in field robotics is the milking of cows. This is a billion-dollar industry. More than six thousand milking robots are sold annually[17]. The milking robots typically reduce the cost of milking a cow by 10%, and at the same time, the machines allow for milking 24/7 with minimum supervision. This is an industry that is seeing 10% annual growth.

Processing of meat is another area that has seen some growth. The main challenge has been the high processing rates and competing with skilled labor. As progress on vision and force-torque sensing evolves, there is a tremendous opportunity to increase automation.

The World Bank states that the world will have to produce 50% more food by 2050 if the global population continues to rise at its current pace[18]. Over the next 15 years, global demand for meat is

[17] https://ifr.org/ifr-press-releases/news/staff-shortage-boosts-service-robots-sales-up-48
[18] https://www.fao.org/fileadmin/templates/wsfs/docs/Issues_papers/HLEF2050_Global_Agriculture.pdf

expected to increase by 40% triggered by a growing number of people adopting protein-rich diets. Crop yields will have to rise by at least as much as crop demand to avoid further encroachment of cropland into natural habitats.

Access to affordable automation that will increase productivity will be essential to enable wider use of robotics and automation in the food sector. Affordable robotic systems equipped with sensors and AI can enable precise monitoring of weather, crops, and soil conditions. This data can be used to reduce fertilization and pest control applications while improving crop yields and quality. Moreover, these systems can improve soil management practices, such as cover cropping and reduced tillage. As a result, robots can reduce greenhouse gas emissions and play an important role in climate change management schemes. Agricultural robots can collect information about carbon dioxide levels, temperature, and humidity, resulting in improved climate models for climate change adaptation and mitigation strategies.

3.4 Aging Society

3.4.1 Introduction

The US population is rapidly aging. By 2020 more than 16% of the population was above 65[19]. By 2030, more than 20% of the population is projected to be above 65[20]. The healthcare industry, representing over a $4.5 trillion economy in the United States and trending towards consuming 20% of the US GDP, stands as the segment with the fastest increase in spending. This highlights a critical area for innovation and improvement. Robotics emerges as a transformative force in this landscape, offering a significant opportunity to reduce costs while making treatment[21] and support[22] smarter, less invasive, and more personalized.

3.4.2. Surgery

As societies age, the demand for healthcare increases. This is true across all segments of healthcare, especially surgery. Surgery can address a third of the global healthcare burden. Yet the majority of the world’s population, approximately 5 billion people worldwide, lack adequate access to surgical care: Even so, over 300 million surgeries per year worldwide are performed, and an additional 143 million surgeries are needed to meet global demand[23]. Given the shortage of surgeons and care staff, this can only be accomplished with robotics. The aging population, for example, is driving up demand for joint surgeries, including those for the knee, hip, spine, and shoulder, necessitating advancements in robotics within orthopedics.

In general, advances in robotic technologies enabled by increased funding are needed to simultaneously improve clinical outcomes, making treatments smarter, less invasive, and more personalized, and to

[19] https://www.census.gov/topics/population/older-aging.html
[20] https://www.census.gov/data/tables/2023/demo/popproj/2023-summary-tables.html
[21] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5607789/
[22] https://www.nia.nih.gov/health/aging-place/aging-place-growing-older-home
[23] https://www.who.int/news-room/fact-sheets/detail/patient-safety

contain and reduce healthcare costs by facilitating more effective and earlier treatments and fostering increased competition in the healthcare sector.

Some early successes in medical technologies and robotics have already enabled shorten hospital stays and ushered in a migration from traditional inpatient treatments in hospitals to Ambulatory Surgical Centers (ASCs) and outpatient facilities. This shift enables increasingly complex procedures, ranging from diagnostic procedures, to knee surgeries all the way to cardiac procedures, to be performed on an outpatient basis without the need for overnight stays. In addition, robotics-assisted surgery and diagnostics have the potential to reduce today's large variability of treatment outcomes, simplify surgeons' training, increase surgeons' productive work life, and reduce today's high rate of post-surgical complications. Increasing adoption of robotics, automation, and AI in healthcare will alleviate the current and future shortage of surgeons, physicians, and nurses

The development of tell-robotics and its application to telesurgery is instrumental in extending access to surgical care to underserved areas, especially for specialty procedures. This demonstrates the vast potential of robotics to revolutionize healthcare by making it more accessible, efficient, and effective in addressing the needs of a growing and aging population both in the US and globally.

In the realm of oncology, lung cancer stands as the number one cancer killer globally. Robotics is crucial in enabling early diagnosis, which is critical to drastically improving survival rates. Robotics enables the increase in diagnostic yield of biopsies and the future, integrating surgical treatment and subsequent therapy via drug delivery to offer a "one-stop diagnose and treat" approach. This has the potential to save countless lives and greatly reduce the total cost of treatment.

3.4.3. Aging in place - Physical Support

In April 2023, the White House issued the Executive Order on Increasing Access to High-Quality Care and Supporting Caregivers in response to the current and growing social and economic crisis in meeting eldercare needs[24]. The growing number of older adults who need assistance, combined with a severe workforce shortage and the high costs associated with eldercare, contribute to this crisis. Recent analyses project there will be 83.7 million people aged 65 or older in 2050; and many of these will need assistance with personal care. We do not have the workforce to provide this care, so we need to develop technology that can provide assistance in the home that is safe, effective, and equitable. Since a one-person-to-one robot operation isn't feasible for widespread use, teleoperation is not the solution – these robots will need to have more autonomy.

Following the pandemic, the eldercare sector is encountering a significant challenge. A critical shortage of workforce, coupled with the considerable expenses associated with eldercare, is rendering care provision increasingly arduous. Nursing facilities are either shuttering or offering subpar services as they grapple with financial constraints and staffing issues. More than 700,000 individuals reliant on Medicaid

[24] https://www.whitehouse.gov/briefing-room/presidential-actions/2023/04/18/executive-order-on-increasing-access-to-high-quality-care-and-supporting-caregivers/

are languishing on waiting lists for home- and community-based care[25]. Family caregivers are contending with many stresses, encompassing mental, physical, and financial strains. Despite the pandemic prompting a disruption in traditional care methods, there has been a notable absence of substantial technological advancements in eldercare. Presently, care services remain predominantly reliant on in-person interactions, with technologists yet to devise a viable alternative to labor-intensive face-to-face care.

The goal of aging-in-place is to postpone or even obviate the need for older adults to transition to nursing facilities, while reducing reliance on hard-to-find professional care providers and promoting the well-being of family caregivers. Ideally, this technology addresses social and economic barriers, such as bridging the digital divide and reducing disparities in healthcare access. Robotic technology that solves this problem will be physically assistive devices that help older adults move, e.g., from bed to wheelchair or to allow bedsheets to be changed. They might also help people dress, use the restroom, and eat. Maintaining mobility and balance is also crucial for seniors to live independently as they age in place. Preserving physical strength and balance requires regular exercise, which can be safely facilitated for frail older adults with appropriate physical aids and assessments (e.g., to proactively identify risks of falling and offer physical support accordingly). These physically assistive devices should be part of a larger aging-in-place support/tele-support system, including digital health monitoring and pre-clinical diagnoses. This integration is essential for facilitating the safe, cost-effective, and pandemic-resilient delivery of rehabilitation, nursing, and care services directly to individuals' homes. The same systems that provide physical assistance can also enable cognitive benefits.

3.4.4. Aging in place - cognitive and emotional support

As the population ages, the social and healthcare systems are strained to support the cognitive, social, and emotional needs of this growing population that stretches across demographics and presents various needs and challenges.

Cognitive decline, dementia, and Alzheimer’s disease will impact one in five residents of the United States aged 65 or older by 2030 (U.S. Census Bureau, 2023)[26]. About 20% of individuals over 65 today already have mild cognitive impairment (MCI), with about 15% transitioning to dementia each year. Over 75% of dementia caregivers are informal, constituting over 16 million in the US, and this number will only continue to grow, representing a global health emergency. Worldwide, approximately 50 million people live with dementia, most of whom are older adults. Finally, in a recent study, the average annual turnover rates of nursing staff at nursing homes in the US were measured as 128% (with the median turnover rate being 94%), demonstrating that these jobs are not sought after or appreciated by human workers.

The loss of function can manifest in a gradual way and over a long time. Early detection, proper diagnosis, and tracking and intervention significantly improve safety and quality of life.

[25] https://www.hrw.org/news/2021/03/25/us-concerns-neglect-nursing-homes
[26] https://www.census.gov/newsroom/press-releases/2023/population-estimates-characteristics.html

While digital technologies such as smartphones are ubiquitous, they become increasingly difficult for seniors to use; embodied personalizable combination robots present a more relatable alternative that can address a wide range of the challenges mentioned above. Specifically, such robots can engage in many daily interactions with the elderly user, providing social and cognitive stimulation, reminders, and information, while also analyzing the user's speech, affect, pose, walk, activity, medication adherence, etc., to look out for early signs of cognitive, emotional, and/or mental health decline.

In addition to screening and early detection, companion robots can serve as coaches for healthy prevention habits and lifestyles by providing personalized motivational challenges and support for activities such as daily walks, healthy eating, relaxation, ample time for sleep, and social connectedness with family and friends, among others. These clinically validated preventive health regimens are known to improve health and reduce risks from heart disease, diabetes, metabolic disorder, insomnia, and mental health issues, but typically require discipline and social support that could be provided at scale with low-cost companion robots. In some communities, such systems may provide significantly improved access to health screening, as well as potentially higher trust as a personalized interface compared to an impersonal health system.

Companion robots can come in various forms, including pets, enabling elderly users to benefit from the known values of pet ownership (companionship, increased activity levels, improved mood) as well as added functionality of a robotic pet (object finding and fetching, other physical tasks) without the complexities of ethical ownership of a live dog.

Such companion robots for in-home use will require natural control interfaces, safe and appealing behaviors that humans readily recognize, understand, and trust, and that are capable of real-time understanding of human state and intent, and engaging in natural language interaction as well as non-linguistic interaction through gesture and body language. With the addition of wearable technology, biometric sensing including physiologic data (beyond heart rate and galvanic skin response on to muscle activity, brain function, vigilance, cognitive workload, fatigue, etc.) would provide an additional level of prevention, user understanding, and support.

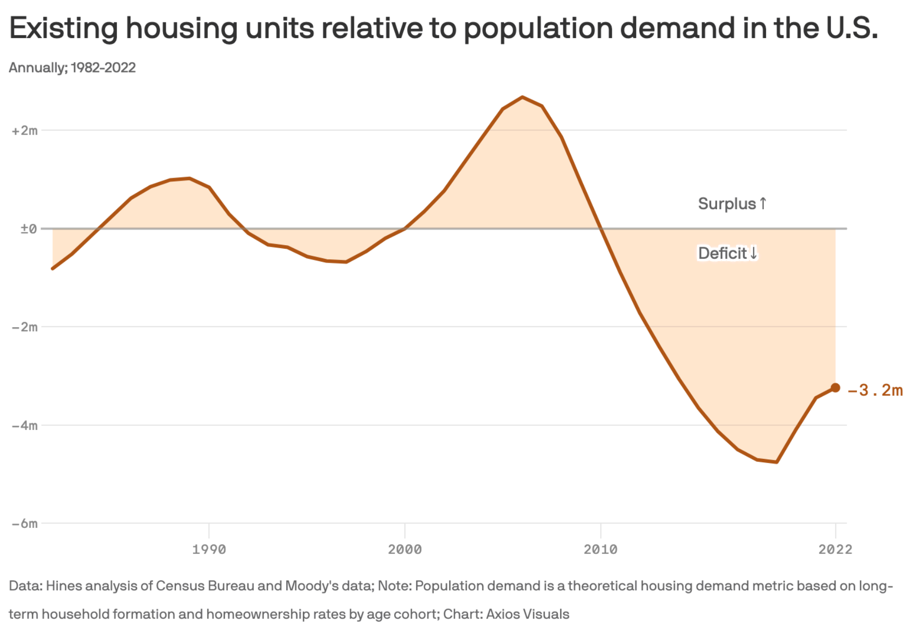
Any in-home systems with perception bring up issues of privacy, safety, and ethics, including data storage and balancing aggregated vs. personal data are all key issues to be addressed across the digital landscape, and especially so in robotics, where the data are highly multimodal and datasets are massive.

The notion of companion robots in the home is complementary with human helpers for the elderly. Human touch and presence is important for elderly physical and mental health, but human caregivers are hard to find and retain[27]. Therefore, by expanding the caregiving capacity with companion robots, the workload on human caregivers is reduced, and the work can be focused on functions that humans are both more motivated to provide and better able to provide.

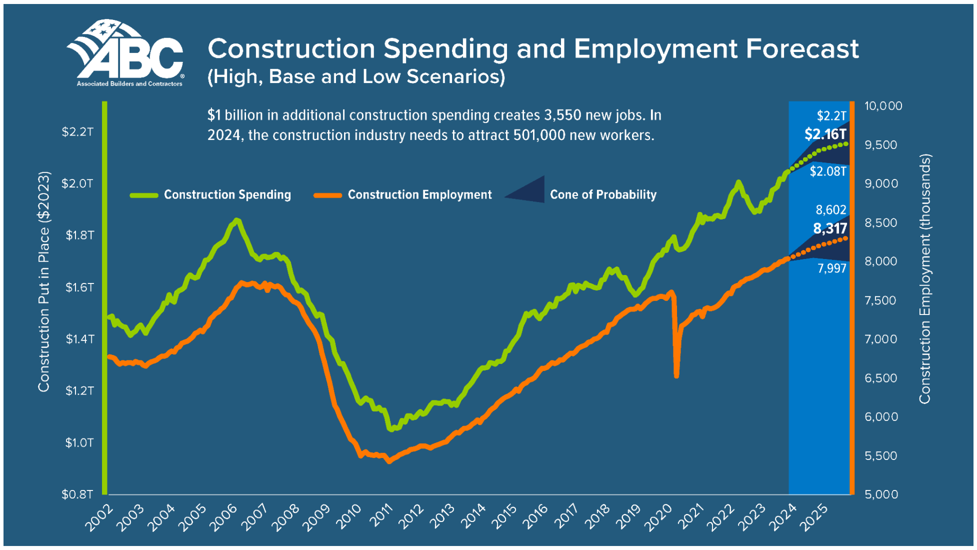
[27] https://www.caregiver.org/resource/caregiver-statistics-demographics/

3.5. Housing & Infrastructure

The US has a housing shortage, with high-demand and low supply driving up prices. Young Americans are unable to buy houses as their parents did; they must also spend increasingly higher percentages of their income on rent, as the number of rental units available is also too low for our population. These increased housing costs caused by a lack of inventory will continue to erode the economic opportunities for American citizens – and the resulting reduction in discretionary spending for millions of Americans will weaken the US economy.



From https://www.axios.com/2023/12/16/housing-market-why-homes-expensive-chart-inventory



From
https://www.abc.org/News-Media/News-Releases/abc-2024-construction-workforce-shortage-tops-half-a-million

One contributor to the lack of housing units is the labor market in construction. Unemployment rates in construction are very low, with the Associated Builders and Contractors (abc.org) predicting the need for 500K new construction workers in 2024 alone to meet the needs of increased construction and retirements resulting from an aging workforce[28]. We see an opportunity for the use of robots to increase productivity in construction, while reducing worker injuries (2.4 per 100 full-time workers in 2022[29]) and deaths (~1K/year from 2019-2022[30]).

Some companies are already exploring the use of robots to help with bricklaying, moving heavy items on construction sites, and framing houses. Robots could also potentially help to reduce waste on construction sites, which is important in the face of the increasing costs of building materials. Just as heavy equipment can be rented for construction, such robots could also be rented to avoid the need for capital investments by builders and contractors.

There are also similar needs for infrastructure in general. Even with the large amounts of funding appropriated in the November 2021 Bipartisan Infrastructure Law, it will likely be difficult to execute its goals with a smaller workforce resulting from an aging US population together with the reluctance of younger workers to take low-paid, dull, dirty and dangerous jobs. Our needs for housing, food, water, energy, transportation, and other areas of infrastructure are great. Robots could help us to meet all of these critical needs in the face of a smaller workforce.

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28 https://www.abc.org/News-Media/News-Releases/abc-2024-construction-workforce-shortage-tops-half-a-million

29 https://www.bls.gov/iag/tgs/iag23.htm

30 https://www.bls.gov/iag/tgs/iag23.htm

- For bridges and roads, robots could conduct inspections and to autonomously repair, pave, grade, stripe and mark roads, all under the supervision of human workers who would move from physically intensive jobs to more supervisory roles. Robots can also inspect and repair other types of transportation infrastructure like subways, trains, airports, and ports.

- Our volume of trash is increasing concurrently with our population size. Robots could sort waste from recycling and organic matter to reduce the amount that is burned or goes into landfills, with this sorting both at local pickup locations and larger sorting centers. These robots could also maximize the resale of some types of garbage as a commodity (e.g., compost).

- In the area of natural resources, robots can help with renewable energy (e.g., construction and maintenance of wind and solar farms), land and mineral management (e.g., mining), and water (e.g., repairing and replacing aging pipes, desalination).

3.6. Sustainability

Opportunities for robotics to support sustainability span multiple areas, that range from manufacturing applications to agriculture, and include development of renewable energy, maintenance of aging infrastructure[31], reducing food waste[32], adapting to a changing climate, as well as quality of life for workers. We list the main ones:

3.6.1. Sustainability in manufacturing

Sustainability of manufacturing requires the ability to automate the handling of hazardous materials to avoid potential harms to workers and the environment (e.g., the lithium required for batteries to electrify transportation). Robots can also provide opportunities for the increased use of sustainable materials. In addition to manufacturing new products, attention has to be devoted to remanufacturing and repairing existing products, automating field service, finding ways to interact with used and dirty parts, and ways of properly disposing of non-reusable parts.

3.6.2. Renewable energy development

The development of solar farms ranges from the design of the layout of the farm, to driving the piles and constructing the solar cells. To maintain the solar farms, cleaning, mowing, and management are needed and can be provided by robots. Similarly, robots can play a major role in the prospecting, construction and maintenance of wind farms, geo-thermal, wave every, nuclear and other alternative/renewable energy sources.

[31] https://infrastructurereportcard.org/

[32] https://www.epa.gov/smm/resources-waste-and-climate-change

3.6.3. Agriculture

Agriculture needs to become increasingly sustainable, given the population growth and the challenges caused by climate changes. Robots can help (e.g., through analysis and targeted application) in reducing and reusing water, and reducing chemical usage to minimize runoff. Another sustainability objective is reducing food waste through more efficient harvesting and distribution.

3.6.4. Adapting to a changing environment

Adapting to a changing environment is another requirement for sustainability, where robots can play an important role. Robotic systems can aid in fighting wildfires, which are becoming more common. Robots can help in mapping fires and directly intervening to extinguish or contain them. The increase in the strength and frequency of hurricanes and tornadoes also requires support from robots in mapping the areas affected, and helping in search-and-rescue operations. Automation is also critical to help farming adapt to a changing climate. For instance, identifying and addressing the northward spread of diseases that affect crops and forests in a warming climate can be supported by robots.

3.6.5. Maintaining aging infrastructure

Robots can be used to inspect and maintain aging infrastructure, like roads, bridges, buildings, dams, railways, and power lines. This maintenance can help prevent collapses that will endanger people and reduce productivity and quality of life for everyone involved.

3.6.6. Maintaining industrial equipment

Equipment such as wind turbines, gas turbines, generators, and even aviation engines are costly and challenging to maintain, often because heavy equipment is required to perform disassembly and reassembly steps after maintenance is performed and also because great efforts are taken to ensure human technician safety. Robotic systems can be deployed to interact with and maintain industrial equipment in ways that human technicians cannot whether it is because of scale, strength or challenging access paths. Such tools will greatly reduce the cost of maintaining the industrial equipment that we rely on in our daily lives.

3.6.7 Sustainable resource collection

Examples of sustainable resource collection that can be enabled by robotics include: the targeted harvesting of sustainable materials (e.g., lumber) with minimal impact to biodiversity; and the collection of metallic nodules from the ocean floor without harming the natural ecosystem[33].

[33] Hein, J. R., Koschinsky, A., & Kuhn, T. (2020). Deep-ocean polymetallic nodules as a resource for critical materials. *Nature Reviews Earth & Environment*, *1*(3), 158-169.

3.6.8. Recycling and waste management

Improved recycling capabilities would reduce the environmental impact of production and reduce waste streams. Robots are required to recycle hazardous materials that are key for environmental sustainability (e.g., lithium batteries). Furthermore, new automation technologies will be key to moving the recycling or reuse of materials beyond those that can be easily automated (e.g., separating metals and paper products) to increasingly complex products (e.g., electronic devices). Such improved recycling would serve a dual purpose of sustainably harvesting precious materials as well as reducing waste streams.

3.6.7 Quality of life for workers

Obviously there is the need to improve the quality of life for workers. Robots can play a large role, including in helping with repetitive hard and dangerous work, which often requires heavy lifting or using dangerous products, allowing workers to focus on the tasks that require human attention. Robots can also improve the safety of workers in manufacturing environments, agriculture, and other roles such as fighting wildfires, all of which are key for improving the sustainability of the economy by improving the quality of life of workers.

3.6.8 Transportation

FInally, sustainability of transportation plays an important role. It has by now been shown that use of autonomous or semi-autonomous vehicles can optimize transportation systems. In addition, it has been shown that smart vehicles can reduce fuel consumption by as much as 20%. Consequently there is a lot of potential in the utilization of intelligent vehicles from micro-mobility to trucks to reduce the environmental impact.

3.7. Expanding Frontiers

The realm of space offers unprecedented opportunities to expand our technological and economic horizons. Already today it is difficult to imagine daily lives without global navigation satellite systems (GNSS). We use it when flying to another city, for tracking packages, and for cell phone-based trekking. There are so many aspects of our daily lives that rely on these global satellite systems. Not to forget, space plays a major role in the future of science.

As we push the boundaries of human presence beyond Earth, several promising avenues are emerging.

Opportunities

1. **Space Mining:** This involves the extraction of valuable resources from celestial bodies such as asteroids and the Moon. Key elements targeted include rare metals like platinum, iridium, osmium, and palladium, which have critical applications in various industries. The potential for mining these resources presents a significant opportunity for economic expansion and technological advancement in space industries.

2. **On-orbit Servicing and Repair**: This sector focuses on maintaining and enhancing satellite operations through refueling, repairing, and upgrading while they are in orbit. Such services can significantly extend the operational lifespans of satellites and enhance their functionality, offering a sustainable solution to manage the growing satellite populations in Earth's orbit.

3. **Space Manufacturing and Recycling**: As space activities increase, so does space debris. Recycling this debris to recover raw materials presents a unique solution that could support manufacturing directly in space. This approach reduces the necessity and high costs associated with transporting materials from Earth to space, facilitating more sustainable extraterrestrial operations.

4. **Space Exploration and Infrastructure**: Developing technologies for habitation and work on the Moon is a critical aspect of modern space exploration. This includes creating sustainable methods for resource extraction and utilization on the Moon, paving the way for long-term human presence and industrial activity.

5. **In-Situ Resource Utilization (ISRU)**: ISRU focuses on using local resources in space environments to support human life and enable the construction of space infrastructure. This technique is vital for long-duration space missions, as it allows for the production of essential supplies like oxygen, water, and building materials directly from local extraterrestrial sources.

Key Differentiators

- **Technological Advancements**: The field of space exploration is rapidly advancing with improved technologies in operations, autonomy, and robotics. These advancements are opening new possibilities for more efficient and extensive exploration and utilization of space resources.

- **Decreasing Costs**: The costs associated with space travel and launch services are continually decreasing. This trend is making space-based activities more accessible and economically feasible, encouraging more frequent and varied missions.

- **Private Sector Involvement**: There is a surge of innovation and investment from the private sector in space-related industries. This competitive energy is driving forward the development of new technologies and making space ventures more dynamic and commercially viable.

- **Resource Scarcity on Earth:** The depletion of Earth's natural resources is a pressing issue, prompting the exploration of space as an alternative source of vital raw materials. This need is accelerating the push for space mining and resource utilization initiatives.

Each of these elements plays a crucial role in shaping the future of space exploration and the expansion of human activities beyond our planet. As we continue to explore these frontiers, the integration of new technologies and innovative approaches will be key to realizing the full potential of space as the next domain for human expansion

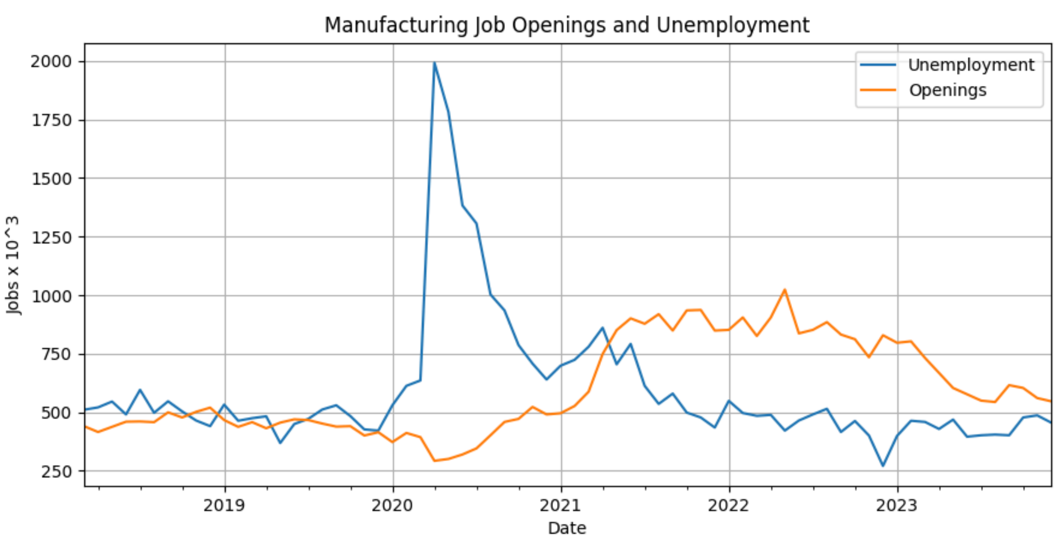
4. Challenges

Frequently it is not directly possible to capitalize on opportunities as outlined in Section 3, as there are unresolved challenges that must be addressed before it is possible to generate solutions. In this section, we will outline some of the challenges across workforce, lean-logistics, easy of use, security and tool chains.

4.1. Workforce

As discussed in Section 2.4, there is a shift in demographics and a projected decrease in the global workforce over the next few decades due to aging populations and declining fertility rates. These changes are expected to have long-term effects.

However, there has also been a recent and rapid transformation in the workforce composition. Prior to the COVID-19 pandemic, the number of trained workers in both manufacturing and warehousing was relatively equal to the number of available positions. This created a balanced supply and demand. However, in the aftermath of COVID-19, this equilibrium has been disrupted. According to the Bureau of Labor Statistics (BLS), there are 300,000 open positions (Feb 2024)in manufacturing that cannot be filled, as well as a similar number of unfilled positions in warehousing[34]. To sustain economic growth, there is a pressing need for either an increase in the workforce or an improvement in productivity to compensate for the shortage of workers.



Job openings in manufacturing vs unemployment reported [BLS.gov]

[34] https://www.bls.gov/jobs/

Even in the short-term there is a dire need to retrain people to work in manufacturing and at the same time we need a stronger effort to provide capacity at trade-schools but also to provide technologies across the use-cases to make it simpler to use in parallel with studies of methods to increase productivity.

4.2. Lot size 1 operations

Lot size 1 manufacturing, or custom manufacturing, involves producing individualized, highly customized products in small quantities, even down to a single unit. Examples include customized apparel, personal electronics devices, automobiles, and home furniture. While this approach provides increased flexibility and caters to specific customer demands, it introduces several challenges.

Customized products often come with heightened complexity and variability, posing challenges in production planning, scheduling, and maintaining consistent quality across different configurations. These complexities motivate the need for more flexible production processes that involve specialized equipment and techniques, which ultimately drive higher unit costs and lead times compared with the traditional approaches to efficiently produce large quantities of identical goods. Once a product has been produced, ensuring consistent quality in customized products is challenging, requiring rigorous quality control measures to meet unique specifications and customer expectations.

Additional challenges to lot size 1 manufacturing relate to supply chain and skill requirements. Managing a supply chain for lot size 1 manufacturing is complex due to the need to source customized components, coordinate with various suppliers, and maintain inventory control becomes intricate compared to traditional mass production. It introduces additional challenges to designing the factory floor with appropriate size and layout to support more flexible manufacturing. Lot size 1 manufacturing traditionally demands a highly skilled workforce capable of adapting to changing production requirements. Training and retaining skilled workers can be challenging.

Robust information technology (IT) systems are essential to support customization, order tracking, and real-time production monitoring. Integrating these systems can be challenging but is crucial for efficiency. Managing customer expectations and communication becomes critical in lot size 1 manufacturing. Clear communication is needed to convey realistic timelines, potential limitations, and factors impacting the customization process.

Adhering to regulatory standards and compliance requirements becomes more complex for some highly customized products related to regulated industries such as healthcare and aerospace, requiring time-consuming efforts to ensure each product meets relevant standards.

Smaller production runs associated with lot size 1 manufacturing may result in higher energy and resource consumption per unit, potentially impacting overall environmental sustainability. However, local manufacturing may reduce emissions related to product transportation.

Despite these challenges, advances in robotics technology, such as adopting advanced manufacturing techniques, automation, and digitalization, can help mitigate some of these issues and make lot size 1 manufacturing more efficient and cost-effective. Specifically, robotics technologies can support greater efficiency in producing lot size 1 goods. Still, several challenges stand in the way including:

1. Customization Needs: Understanding the needs for customization, whether driven by functional requirements or personal preferences, and the tradeoff between customization and cost, including development, deployment, worker training, and recertification.

2. Robotics Limitations: Current robotics face challenges in supporting the vision of lot size 1 manufacturing due to programming complexity, limitations in perception, planning, and control, as well as constraints in mobility, sensors, and grippers on the factory floor.

3. Human-Robot Collaboration: For the foreseeable future, humans and robots will likely collaborate to create unique products. However, the state of human-robot interaction (HRI) does not yet fully support complex and variable manufacturing tasks safely.

4.3. Zero Learning Curve

For robots to be widely adopted and effective, they must be immediately useful, without requiring the user to learn and adapt to the system. Analogously, the system should be able to adapt to the user's preferred modes of work and use, for continued efficacy and to prevent abandonment.

While research has studied interfaces for system setup and for entering user preferences, considering these challenges in the robotics context is a new problem because many of the preferences are inherently embodied and situated in an environment, so they arise in the course of interaction. This means robot systems must have sufficient initial functionality to begin to operate reasonably well, and must also be able to continue to adapt and provide options to the user. To inform users about other capabilities, robots could be developed with tutorial modes that allow the systems to be immediately useful while teaching people new capabilities that the system thinks could be useful.

Home robots are a particularly challenging sector of service robotics because of the vast variety of home environments, use cases, and user backgrounds and preferences. This means home robots must be able to adapt to the particular home and user/family needs by on-the-job learning, and such learning must happen quickly at the start, to avoid delays in effectiveness and user frustration and time-waste, as well as continue indefinitely, to be responsive to changes is user needs and preferences that may happen at any point. The first requirement is often referred to the "out of the box experience", the ability of a product to be immediately useful. For home environments, it is likely that robots will need some user input to learn key needs and preferences, but the number of queries and options at setup time needs to be small while also allowing users to dynamically choose to add as much information as they desire, as well to correct/update the system's functionality continually. Another change for in-home systems is the need to be able to operate with multiple users who may have different preferences; this requires the ability to accurately recognize all users and act and adapt accordingly.

In the workplace, robot systems should be immediately useful to their human counterparts, with the ability to teach additional features in-situ. For example, imagine a collaborative robot system in a factory that can bring parts for a human to assemble. The first day that the worker encounters the robot, the arrival of parts should occur as needed and delivered similarly as would be expected from another person. Over time, if the worker's assembly task encroaches into the robot's delivery area, the robot could use some form of light projection to convey to the person what needs to be done differently.

Whether in the home or workplace, robots should ultimately be "invisible in use", providing seamless service that does not add cognitive burdens on the user.

4.4. Sustainable Economy

The world around us faces various challenges with climate change, feeding a growing population, and reducing the human impact on the environment. Sustainability is a key topic where robotics can play various roles. Moreover, robotics and a sustainable economy are intertwined. Robots are key in addressing key challenges with a sustainable economy in some profound ways:

- Agriculture and Sustainable Economy: Reducing the use of pesticides and fertilizers is a big challenge with significant financial and environmental implications. Managing scarce water resources as the world is facing extensive droughts, increases in average temperatures, and deforestation is critical. Agricultural robots (e.g., drones, ground platforms) can assist in rapid plant health assessment, detect early signs of plant water deficits, and reduce soil erosion. The big challenge remains in how the robots can be used to increase crop yields with reduced environmental impact and improved food security.

- Sustainable Transportation: The transportation sector needs a set of interventions that will lead to more sustainable and energy-efficient transportation systems. Robots and autonomous or semi-autonomous vehicles can lower greenhouse gas emissions, reduce traffic congestion, and lead to improved and sustainable usage of transportation infrastructure and networks.

- Robots in Circular Economy: There is a growing emphasis on circular economy. The European Commission estimates that the circular economy could create 700,000 new jobs and boost the EU's GDP by 0.5% by 2030[35]. Key functions of the circular economy such as recycling, refurbishment, and remanufacturing can be done with robotic systems that can sort objects, disassemble electronic items, and obtain valuable material from disregarded resources. Addressing challenges in perception, human-robot interfaces, and manipulation can empower robots to execute tasks that facilitate the recovery and reuse of resources.

- Supply Chain Resilience: Robots are pivotal in improving the resilience of supply chains by increasing the use of recycled resources instead of focusing on scarce resources that need to be transported from remote locations. Moreover, robots can improve the safety of workers who

[35] https://ec.europa.eu/commission/presscorner/detail/en/qanda_20_419

are involved in often hazardous operations to sort materials and resources that often contain higher levels of dangerous chemicals and environmental pollutants.

- Resource Efficiency and Robots: Manufacturing is an area where reducing waste and improving production efficiency is critical. Robots can be effective in doing repetitive movements while minimizing errors. It should be noted that effective resource management can lead to a more thoughtful and sustainable use of natural resources while the environmental impact is reduced.

- Renewable Energy Production and Maintenance: Installing and maintaining solar panels and wind turbines is a process that can be improved using robots. Thus, the transition to a low-carbon economy and the reduction of reliance on fossil fuels can be more realistic with easily tangible outcomes.

- Robots and Infrastructure: Improving the safety and longevity of critical infrastructure elements such as bridges, water treatment plants, highways, etc. is a key objective of governments and state agencies. Drones and ground platforms can help in the various steps of the lifecycle of these infrastructure elements. The ultimate goal is to have a more sustainable built environment.

4.5. Privacy/Security/Trust/Safety

The evolving landscape of robotics presents unique challenges, particularly in the realms of privacy, trust, and safety. Each of these areas encompasses several nuanced issues that must be addressed as robots become more integrated into our daily lives.

4.5.1. Privacy Concerns with Robotics

Privacy becomes a pressing issue as robots equipped with advanced sensors are increasingly used in various settings, from public spaces to the privacy of one's home. These robots can easily record and store large amounts of data, raising questions about how to maintain personal privacy. A fundamental challenge is how to obtain meaningful consent from individuals who may not fully understand the technology's implications. This consent must be nuanced to reflect the complex situations in which robots operate, especially when they encounter bystanders who have not agreed to be monitored. Jurisdictional differences further complicate the regulation of these technologies, as laws vary significantly across regions. Addressing these privacy concerns requires a collaborative effort involving legal experts, technologists, and policymakers to create regulations that protect privacy without stifling innovation.

4.5.2. Building Trust in Robotic Systems

Trust is another critical factor in the adoption of robotic technologies. Establishing an appropriate level of trust—neither too little nor too much—is essential to prevent both overreliance and undue skepticism. The behavior of robots and the transparency of their operations play significant roles in shaping trust. Collaborations with social psychologists could help determine the observable behaviors that foster trust. Additionally, transparency about data collection and usage is crucial, particularly when inscrutable technologies like deep learning models are employed. Explaining robotic decisions in a meaningful way, rather than through opaque methods, will be key in building trust.

4.5.3 Integrating Robotics into Society

The integration of robotics into the workforce and everyday tasks also presents numerous challenges. The fear of job displacement is a significant concern as robots are poised to replace some human roles, despite potential overall job gains. It is crucial to address these fears honestly and transparently. Deciding which tasks to automate should consider the personal and social value of these tasks, avoiding automation of jobs that are meaningful to many individuals. This requires careful consideration of how robots integrate with and complement human workflows without causing disruptions.

4.5.4. Security and Safety Standards

Security issues particular to robotics include vulnerabilities that are not present in traditional cybersecurity. The physical abilities of robots to interact with the real world mean that their theft or misuse could have direct physical consequences. This raises the need for robust security measures that go beyond traditional digital safeguards, addressing unique challenges like voice-command hijacking and emotional manipulation through robots with which users may form affective bonds. Safety standards, too, must evolve to account for the use of machine learning in robots, ensuring that these systems meet rigorous safety certifications traditionally reserved for more predictable, deterministic systems.

4.5.5. Policy and Research Recommendations

To effectively address these complex issues, it is crucial to foster greater expertise in government on cyber-physical systems and support interdisciplinary research. This includes breaking down silos between different areas of expertise and removing legal and bureaucratic barriers to research. Additionally, creating harmonized safety standards across jurisdictions would facilitate smoother development and broader adoption of robotic technologies.

As robotics continues to advance, the intersection of technology with legal, ethical, and social considerations becomes increasingly important. Policymakers, researchers, and industry leaders must work together to ensure that the expansion of robotic technologies benefits society while mitigating potential harms. This multifaceted approach will be essential to realizing the full potential of robotics in a way that respects privacy, fosters trust, and ensures safety.

4.6. Digital Production / JIT (Design - Simulation - Delivery)

Digital fabrication is a set of production processes that can automatically produce 3D parts from digital 3D models (produced using computing-aided design, or CAD). Digital fabrication uses robotic systems to automate additive and/or subtractive manufacturing. Broadly, manufacturing approaches are categorized as additive, subtractive, and forming. Additive fabrication technologies include various types of 3D printing (Fused Deposition Modeling, Stereolithography, Digital Light Processing, etc.) and other methods like knitting. Subtractive fabrication techniques involve removing material to obtain new geometry, and examples are laser cutting, Computer Numerical Control (CNC) machining, and Electrical Discharge Machining. Forming fabrication involves reshaping materials through deformation, and includes casting, forging, extrusion, and molding. All of these methods require a physically moving element that is controlled to precisely add, subtract, or form material. Thus, all digital fabrication technologies are inherently robots, because perception, planning, and actuation are combined to translate digital design data into physical action to perform fabrication.

The most popular type of digital fabrication is 3D printing (a type of additive manufacturing) which creates an object by sequentially adding material using various approaches, such as: selectively fusing powders or filaments, or curing polymers with UV light. 3D printing has increased in capability from its appearance in the 1980's consisting of industrial machines that worked primarily with a single material, to the current day where desktop 3D printers can work with a variety of materials (sometimes within the same part). Recent specialized commercially available 3D printers exist to print with exotic materials including titanium, concrete, textiles, cells, and food.

The advantages and disadvantages of 3D printing technologies vary depending on the specific technology used. In general, 3D printing is advantageous because it (1) can create novel geometries and topologies, (2) can be achieved with a wide variety of materials, and (3) generates little waste (compared with subtractive methods). However, 3D printing often suffers from slow speeds of fabrication, small print sizes, low resolution of parts, poor surface finishes, inhomogeneous and anisotropic mechanical properties, and onerous post-processing steps. Recent and emerging robotic technologies that can meet the challenges of modern 3D printing include:

- Robust control or learning in the face of unknown and/or varying environments can enable fast, accurate 3D printing despite changing material or structural properties (i.e., in the substrate, print material, and configuration of the robot doing the printing)[36]
- Planning, control, and learning methods can speed up the printing by a single printhead[1]
- Robotic printheads using novel kinematics such as long, slender, curved paths to access heretofore unreachable locations in the print space (i.e., spaces that could be reached by line of sight)
- Multi-robot systems methods that optimize the use of multiple robotic printheads which may or may not be physically connected (e.g., flying drones that act as 3D printheads[37])

[36] Wang, C., Tan, X. P., Tor, S. B., & Lim, C. S. (2020). Machine learning in additive manufacturing: State-of-the-art and perspectives. Additive Manufacturing, 36, 101538.

[37] Hunt, G., Mitzalis, F., Alhinai, T., Hooper, P. A., & Kovac, M. (2014, May). 3D printing with flying robots. In 2014 IEEE international conference on robotics and automation (ICRA) (pp. 4493-4499). IEEE.

- Approaches to fabricating fully functional robots with embedded control systems on a desktop 3D printer out of a single material[38].

Example applications of advances in digital fabrication

A primary advantage of digital fabrication technology is rapid and customizable fabrication of goods as required to achieve the “now” economy. There is also a strong potential connection to Generative AI where rapid fabrication tools can be used to realize designs created by AI tools physically. A promising application area is medical devices, where the rapid fabrication of customized devices opens many promising opportunities.

> **Patient-specific On-Demand Smart Surgical Implants:** With the targeted advances in medical grade prototyping, surgeons will be able to create detailed, patient-specific models of orthopedic implants, grafts, bones, and joints. Unlike today, where large inventories are needed to accommodate the large variation in patient anatomy due to the long lead time for manufacture, on-demand interoperative printing will allow for precise customization and patient fit. This will eliminate the need for inventory and result in a major cost reduction of orthopedic care. With progress in multi-material printing and integration of sensing, electronics, and communication devices, these implants will measure and communicate implant strain, state of healing, presence of infection, and other key health indicators.
>
> **Patient-specific Surgical Models**: Surgeons can use rapid prototyping to create detailed, patient-specific models of organs, bones, or other anatomical structures based on medical imaging data. These models can serve as practice aids for complex surgeries, allowing surgeons to plan and simulate procedures in advance, thereby reducing operation times and improving patient safety.
>
> **Customized Prosthetics and Orthotics**: Rapid prototyping can revolutionize the creation of prosthetic limbs and orthotic devices by allowing for the customization and production of items that perfectly fit the unique anatomy of each patient. This approach not only improves the comfort and functionality of prosthetic and orthotic devices but also accelerates the manufacturing process, making these essential aids more accessible and affordable.
>
> **Bioresorbable Surgical Implants**: Leveraging rapid prototyping, researchers can develop bioresorbable implants that gradually dissolve in the body, eliminating the need for a second surgery to remove the implant. These implants can be used for various purposes, including supporting broken bones, drug delivery, and enhancing tissue regeneration. Rapid prototyping allows for the precise design and fabrication of these implants to match individual patient needs, improving recovery outcomes.

[38] Zhai Y., De Boer A., Yan J., Shih B., Faber M., Speros J., Gupta R., Tolley M. T. (2023) "Desktop Fabrication of Monolithic Soft Robotic Devices with Embedded Fluidic Control Circuits", Science Robotics, 8 (79), eadg3792.

Customized Drug Delivery Systems: Next-generation rapid prototyping technologies can be used to create customized drug delivery devices, tailoring the dosage, release rates, and form factor to the specific needs of each patient. This application can be particularly beneficial for patients requiring combination therapies or those with unique physiological conditions that affect drug metabolism.

Wearable Health Monitoring Devices: With rapid prototyping, developers can quickly design, iterate, and produce wearable devices that monitor various health metrics, such as heart rate, blood pressure, glucose levels, and more. These devices could be tailored to fit the wearer comfortably and be equipped with features designed to address specific health conditions, providing real-time data to both patients and healthcare providers to inform treatment decisions.

5. Research Opportunities

In this section, the research opportunities to be addressed to solve the challenges outlined in Section 4 and deliver on the opportunities outlined in Section 3 are analyzed. The section addresses issues related to embodiment, manipulation, perception, control, planning, Edge AI, machine learning and human interaction.

5.1. Physical Embodiment

Embodiment refers to the fact that intelligence (whether robotic or biological) cannot merely exist in the form of an abstract algorithm but requires a physical body to interact with the world. Robotic systems exhibit embodied intelligence, which expands the computational framework of the robot beyond the processors into the architecture of the body. The theory of morphological computation describes how the materials and structures of the body (biological or synthetic) process mechanical stresses to reduce the computational load on the brain or computer. In some cases (i.e., reflexes), an appropriately designed body can respond without any processing. In other cases, an extremely difficult computational task (e.g., controlling the positions/forces of five fingers to grasp a delicate object without breaking it) can be greatly simplified by a body structure that incorporates soft and elastic materials (e.g., skin, cartilage, muscle, fat) and compositions (e.g., a single tendon that moves multiple finger joints). Taking inspiration from biological examples, it is possible to take advantage of similar approaches to design robotic systems with a higher level of robustness, agility, and ability to interact safely with humans than traditional designs based actuated systems composed of rigid links. Physical embodiment also has a fundamental impact on social interaction, as it conveys key information through facial expressions, gestures, and body language, all of which are critical in a wide variety of both physical and social human-robot interactions.

5.1.1. Soft Robotics

The emerging field of soft robotics aims to design, fabricate, and control robotic systems that employ soft materials and structures to simplify their interactions with the world by taking advantage of morphological computation[39]. Examples include soft grippers that can easily adapt to a wide variety of objects[40], robots with discrete soft components that allow them to safely interact with humans, and continuously deformable soft robots that can directly interface with humans for rehabilitation[41] or

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[39] Rus, D., & Tolley, M. T. (2015). Design, fabrication and control of soft robots. *Nature*, *521*(7553), 467-475.
[40] Brown, E., Rodenberg, N., Amend, J., Mozeika, A., Steltz, E., Zakin, M. R., ... & Jaeger, H. M. (2010). Universal robotic gripper based on the jamming of granular material. *Proceedings of the National Academy of Sciences*, *107*(44), 18809-18814.
[41] Rodríguez-Fernández, A., Lobo-Prat, J., & Font-Llagunes, J. M. (2021). Systematic review on wearable lower-limb exoskeletons for gait training in neuromuscular impairments. *Journal of neuroengineering and rehabilitation*, *18*(1), 1-21.

medical operations[42]. However, by relaxing the assumption of rigid bodies, soft robots require more sophisticated materials and approaches to manufacturing, modeling, and control as compared to their rigid counterparts. New approaches are required in all of these areas to achieve the goal of robots that are as versatile as biological embodiments, such as the octopus or the elephant. Conversely, there is an opportunity to use new design and fabrication approaches, such as generative design and multi-material additive manufacturing, to go beyond bio-inspiration to enable heretofore unrealized physical capabilities of robots. Personalized robot designs that judiciously incorporate both soft and rigid components, as well as seamless transitions between them, are tied to new opportunities in digital production and just-in-time manufacturing.

5.1.2 Actuation and Power

Creating actuation and power systems for robots that are high-force, long-lasting, and low-cost is an ongoing research challenge. Animal muscles and metabolism are often cited as a gold standard, which engineered systems have yet to match. Electromagnetic actuators are attractive for most traditional rigid robots, but power-to-weight ratios need to be improved, especially given limited battery capacity and the additional weight imposed by batteries. Hydraulic actuation systems are often used for systems with high-power requirements, but their portability has been limited in application to mobile robots. Pneumatic actuators are extremely popular in soft robotics because of their lightweight transmission, but open challenges that require additional research include portability of the sources and accurate control given the compressibility of air. Finally, smart materials including electroactive polymers and Hasel actuators[43] are promising in terms of power-to-weight ratio but tend to generate smaller forces and displacements, and require specialized power sources that are different from those in standard robot control systems (e.g., they typically require much higher voltage). Robot embodiments would greatly benefit from new breakthroughs in actuation technology and power storage/delivery systems to enable longer-term mobility while maintaining safety and strength.

5.1.3. Sensing

Sensing is a key challenge for all robots, but especially for soft robots. Biological organisms have extremely dense sensing (e.g., the human fingertip is innervated by 241 afferents per square centimeter[44]), which they use both for exteroception (sensing the outside world) and proprioception (sensing themselves). By contrast, traditional robots have a relatively small number of sensors (minimally one sensor per joint). Flexible and soft sensors have the potential to enable a much richer understanding of how a soft robot moves and interacts with the world. More work is required to improve the integration of sensors with soft robots, perform sensor fusion to integrate information from different types of sensors, and to efficiently use this information to model soft robots and control them to

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[42] Runciman, M., Darzi, A., & Mylonas, G. P. (2019). Soft robotics in minimally invasive surgery. *Soft robotics*, *6*(4), 423-443.
[43] https://onlinelibrary.wiley.com/doi/full/10.1002/adma.202003375
[44] https://journals.physiology.org/doi/full/10.1152/jn.00313.2020

perform tasks like delicate manipulation, moving through confined spaces, and safely interacting with humans.

5.2. Manipulation

Current robotic manipulators have a high upfront cost and while they perform reliably and efficiently on specific, constrained tasks, they lack versatility and adaptability to new tasks. Programming contributes to these costs and does not translate well to adjacent manipulation tasks. Programming complexity is often minimized by physical optimization of a manipulator for a given task, which tends to reduce physical versatility.

These shortcomings of high-cost and poor versatility may be addressed through a series of research activities to be pursued over a multi-year horizon.

At the forefront of this endeavor is the development of Advanced Gripping Mechanisms. This initiative seeks to harness the concepts of biomimicry and soft robotics to craft versatile gripping mechanisms. These advancements are not only about embracing the complexity of natural inspiration but also about exploring new materials characterized by their remarkable flexibility and adaptability. Such materials are crucial for enhancing manipulation capabilities, especially in unstructured environments where precision and adaptability are paramount. Along another research direction, Unconventional Gripper Designs, which are mainly function-oriented, are also bringing opportunities to the table of robot manipulation.

Parallel to this, the enhancement of Advanced Tactile Sensing is needed. The objective is to equip robotic manipulators with tactile sensors that provide real-time feedback, thereby significantly improving grasping precision and reliability. Achieving this goal necessitates the development of tactile sensors that are dense, robust against wear and tear, and capable of covering the manipulators completely. Complementary, sophisticated algorithms must be created to interpret these dense sensing signals into actionable motion strategies that facilitate precise, versatile manipulation.

Learning-based Control Strategies are also of key importance. Through the application of machine learning and reinforcement learning techniques, the aim is to enable robots to adaptively control manipulation tasks and learn new skills through trial and error. A critical aspect of this approach is the ability to transfer learned skills across different robotic platforms, thereby enhancing the versatility and efficiency of robotic systems.

In the realm of Human-Robot Collaboration, research is required to develop collaborative robotic systems designed to operate safely alongside humans in shared workspaces. This involves investigating natural language processing and gesture recognition technologies to enable intuitive communication between humans and robots. Additionally, a significant focus is placed on implementing safety mechanisms that ensure seamless interaction and collaboration.

Another critical area is Dexterous Manipulation in Complex Environments. The goal here is to augment robotic systems with enhanced manipulation capabilities suited for cluttered and dynamic settings. This includes developing advanced algorithms for path planning and obstacle avoidance, as well as exploring the integration of multi-modal sensing technologies, such as vision, touch, and force, to ensure robust manipulation under various scenarios.

At the core of robotic manipulation research, fundamental algorithms of planning and control are still the major driving force for the field to advance and are far from being good enough. Solid development of fundamental algorithms will not only improve the robustness, efficiency, and usability of robots in daily tasks, but also will provide a much stronger support for new manipulators and sensor designs to be seamlessly integrated into real-world physical applications. Meanwhile, significant values are expected in how fundamental algorithms can enable the large learning-based models to explore themselves, such as data collection, and training through trial-and-error

Lastly, a course needs to be charted towards Autonomous Robotic Manipulation. This ambitious goal involves working towards a high level of autonomy in robotic manipulation tasks by integrating sophisticated perception systems for object recognition and scene understanding. Key to this effort is the development of algorithms that enable autonomous decision-making and task planning, based on the nuanced understanding of the environment and objectives. Additionally, there's a focus on crafting dynamic grasping and manipulation strategies that can adapt to unforeseen challenges, much like the dynamic adjustments seen in successful legged locomotion.

Through this multifaceted approach, the robotics research community is poised to address the current limitations and unlock new potentials in robotic manipulation, paving the way for more adaptive, efficient, and collaborative robotic systems.

5.3. Perception

Perception is the key modality for connecting robotics to the physical world. It would be impossible to perform most daily tasks without vision, haptics, tactile perception, and hearing. Robotic perception also includes sensors that are not biological analogs but instead are designed for specific situations and tasks. For this section, perception is taken to include the acquisition and interpretation of data from sensors which includes sensors that produce images (RGB, IR, Depth, plus medical modalities), domain-specific modalities such as OCT or radar, haptic and tactile perception, sound, and potentially other unstructured information channels.

Computer vision is often viewed as the primary sensory modality in robotics. It has manifold uses -- it can be used to compute geometry (where), identify structures in the environment (what), analyze movement, or support control. Some of these problems overlap with the objectives of the broader computer vision community, and others are unique to robotics.

No matter what the problem is, computer vision (and image interpretation broadly) has been transformed by machine learning (in particular deep learning) over the past decade. For example, the error rate on image classification performance on ImageNet, a standard benchmark, has gone from more than 25% a decade ago to unbelievable percentages of below 5%[45] – a factor of two better than human

[45] https://paperswithcode.com/paper/omnivec-learning-robust-representations-with/review/?hl=112988

performance. Similar trends have been observed in many related problems -- video activity recognition, object detection, image captioning, cancer detection, semantic segmentation, etc. At the same time, the ability to embed these capabilities into a low-power platform has been accelerated by the adoption of these technologies in mobile phones and automated driving systems. Access to these capabilities has been transformed by the development of open-source tools such as Pytorch. It is now quite possible for someone with rudimentary skills in Python to read online tutorials, download code, and field a state-of-the-art vision system. The latest transformational development comes from the successes of Large Language Models (LLMs). Computer vision enhanced with LLMs can create significant advancements in image generation from text, Visual Question Answering (VQA), object detection and segmentation, multimodal representation learning, and image editing and manipulation.

While vision has advanced rapidly, many of these advances have been tied to the availability of large, curated, and labeled data sets. While in principle these same advances can be applied to other tasks and other sensing modalities, progress has been more limited due to structural limitations (e.g., regulatory limitations in the medical area, more limited deployment of IR or depth cameras, or simply lack of a cost-effective mechanism to obtain labels). This has motivated substantial interest in other means for obtaining data and/or transferring learned models from domains that are data-rich to data-poor domains.

Haptics has seen more incremental progress over the past decade. This is due to a number of factors including the lack of wide-spread tactile sensors and displays as well as the complexities of embedding haptics and force feedback in control. Much of the recent interest in this area has been driven by the desire to use haptics in commercial devices such as vibrotactile displays in mobile phones or cars. Research is equally focused on understanding human tactile and haptic perception as on technology development. However, commercial tactile sensors and haptic displays are largely unchanged over the last decade.

Computer vision will continue to advance in terms of the breadth of problems and available tools due to the diverse set of application areas. However, robotics poses unique challenges for computer vision in terms of reliability and speed. Many of the latest computer vision systems have performance that is remarkable compared to the past but operate at an error rate that is well below what is necessary to support reliable long-term robot operation. For example, an automated driving system that fails to detect a person and their intentions in front of the car 1% of the time or which operates with a one-second delay, or a home robot that mis-grasps an object 5% of the time, or a medical robot that mistakes the liver for the spleen 1% of the time is unacceptable.

There are several key areas of progress in perception needed to advance robotics. These include the following:

- **Complex, high dimensional inference**: The broader computer vision community does not always concern itself with classes of problems relevant to robotics. For example, predicting grasps on objects from images is a high-dimensional continuous problem. High-performance approaches and architectures (and data sets) for such problems will likely differ from those popular for recognition or detection tasks. The problem is exacerbated by the new advancements in AI and LLMs that often result in systems that operate like "black boxes." In other words, the black box models that lack transparency can impede accountability and trust which are so critical for robotics.

- **Cybersecurity and computer vision**: Adversarial attacks can impact computer vision systems resulting in incorrect predictions and misguided inferences. Making sure that cybersecurity measures are fully integrated into the design of these systems is essential. Approaches that involve modules like adversarial training, and input validation can assist in the mitigation of these risks.

- **Active Perception**: At the same time, computer vision passively explores data -- it does not take advantage of the ability to actively sense and/or capture redundant information. Part of creating systems that act in the environment will be creating systems that can actively observe to improve their performance.

- **Open-world Performance**: Most computer vision systems adopt a closed-world assumption -- because they are learned from data, the data set represents the totality of examples the system is trained for. Robotics will often be faced with stimuli that have never been experienced, or task variations that are entirely new. Being able to generalize to new contexts and tasks is an open problem.

- **Integratable with Systems**: To integrate vision with other systems, they need to be able to provide an assessment of their internal performance. This includes both methods for verifying or validating a vision component or vision-based system, and methods for systems to return something related to their reliability and uncertainty.

- **Systems Structure**: It is possible to perform reinforcement learning of a task from images in an end-to-end fashion. However, such an approach is not amenable to transfer to similar tasks or similar contexts. Conversely, a more traditional approach would be to separately train computer vision modules from action modules. However, adapting modern learned computer vision modules to action or planning suffers from the reliability limitations outlined above.

5.4. Control

Safe control: safety is the fundamental requirement for robotic systems. Control barrier function and temporal logic-based tools and techniques have become increasingly popular for controller design of safety-critical systems such as robot manipulators, drones, and autonomous vehicles. There remain many open problems in extending the safety controller design into highly nonlinear robot systems, high-dimensional systems, multi-robot systems, and human-in-the-loop systems. With a surge in learning-based controllers in robotics, there is a growing need to certify safety of such data-driven controllers. Safety controllers often come with high computational load, and it is important to ensure real-time performance of such controllers so they can be implemented on an embedded controller or edge computing unit.

Bio-inspired control: Biology offers great inspiration for controller design for robots and complex systems. Experimental studies on octopus limbs and elephant trunks have revealed their distributed control strategies have been integrated into controller design of soft robotic manipulators. Collective behaviors of ants have inspired the controller design for swarm robotics. Much more work needs to be done to identify new biological mechanisms for controller design, build large-scale dataset for the robotics research community, extract information for rigorous controller design, and consider the limitations of the robot's sensors, actuators, and communication systems.

Control of systems with high dimensions and discontinuity: robots are built with increased degrees of freedom and deployed in complex environments. As an example, a full humanoid robot can have more than 40 degrees of freedom. Design of controllers to coordinate all the joints of such robots to perform functional tasks remains an open problem. Robots need to physically interact with humans and environments in real-world tasks, such as human assistance/augmentation, grasping and manipulation, and search and rescue, and such contacts often result in jump/discontinuity of system states. Controller synthesis of hybrid systems needs to be explored for robots for successful field deployment.

Co-development of robot mechanism, control, and learning: conventional robot development starts with the mechanism designs, and controller design does not start until a prototype is built. This paradigm causes a long development timeline and leads to suboptimal robot performance. Future robots call for synergy between material selection, mechanical design, controller design, learning, perception, and testing, so that the overall performance of the developed robots can be optimized and ready for real-world tasks. Control systems play a key role in connecting the design and learning component, and fundamental research is needed for certification of robot performance to support the mechanism-control-learning co-design. This direction is fundamental to reliable, trustworthy, and safe robotics based AI systems of the future.

5.5. Planning

As robots continue to move out of the laboratory and into the real world they will continue to need planning and control algorithms that better deal with the unstructured, unpredictable, and more complex situations in which they will find themselves. They will need to work safely and robustly in the presence of humans, and integrate with existing workflows. Mobile robots with arms, and humanoid robots will need full-body planners, where manipulation, grasping, and movement through the world are harmonized. Robots are also starting to deal with more complex objects that are deformable, fragile, and hard to handle, and we must extend current techniques to deal with these.

While control and planning have traditionally been addressed as separate problems, we will increasingly have to deal with them together, to ensure efficient, fluent movements for our robot systems. This, along with having to plan for more complex environments and robots, means that we will also need increases in the computational efficiency of our planners, taking advantage of technologies such as GPUs.

Scalability of planning algorithms remains an important area of research. For instance, current multi-agent path finding (MAPF)1[46] algorithms can generate paths for multiple robots and ensure there will be no collision, but do not scale up to the hundred of robots needed for large warehouses.

The interest in personalization of products to individual customers will provide new opportunities for the development of planning algorithms that will deal with variations of the plan which could be minor, such as changing a color, but could also be major, such as creating a different sequence of steps in the plan.

5.5.1 Planning Under Uncertainty

Our robots are now leaving the laboratory and performing useful work in the real world. This means that they have to deal with the messiness and uncertainty of this real world. Our planning approaches need to be robust to this uncertainty: movements do not always succeed, objects are not where they should be, sensors are imperfect, lighting is inconsistent, etc. More research is needed in areas of planning that directly address these problems, prioritizing probabilistic approaches and ones that do not rely on accurate high-fidelity models of the world.

Dangerous environments where robots could be deployed will require new attention to how to deal with errors that occur at execution time, but also more attention on how to predict error situations, assess the gravity of the potential error and its impact on the viability of the robot operations, to avoid a full breakdown of the robot and interruption of the process.

The traditional model of offline planning and real-time execution does not work particularly well in dynamic environments. Online planning can suffer from being myopic and missing solutions that are more complex but optimal. Finding a balance and a clear characterization of different approaches remains an important open problem.

5.5.2 Safety in Human Interaction

Research is needed in planners that not only plan to achieve a particular goal, but do so safely, and in the presence of human co-workers or bystanders. Many current planners only consider the robot itself and a limited model of the surrounding things, and emphasize efficiency. As we see more and more robots enter spaces where humans are present, we need systems that take these humans into account, balancing efficiency and safety as they decide what to do.

Transparency and explainability remain open research problems. Being able to introspect on plans and the planning process will be required if the plan has to be explained to non-technical humans, but also to sophisticated users if the plan is complex and not intuitive.

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[46] Roni Stern, Nathan R. Sturtevant, Ariel Felner, Sven Koenig, Hang Ma, Thayne T. Walker, Jiaoyang Li, Dor Atzmon, Liron Cohen, T. K. Satish Kumar, Eli Boyarski, Roman Bartak "Multi-Agent Pathfinding: Definitions, Variants, and Benchmarks", Proceedings of the Twelfth International Symposium on Combinatorial Search (SoCS 2019).

There is also a need for planners that explicitly work with humans, forming collaborative plans that allow tasks to be performed by human-robot teams. More research is needed in the modeling of human activity, intent recognition, and legible motion. Working with or alongside a robot should feel the same as working alongside another human; the movements should be interpretable and "make sense", which at the same time being efficient and purposeful. The plans should be reactive to the movements of the human, and adapt in real-time as the task is being completed. Ideally, these human-robot teams should "just work" and require no training for the human partners.

Doing joint human-robot planning will open up new research opportunities on how to create collaborative plans, where humans and robots collaborate directly on the same tasks, but also on how to split the work between humans and robots, ensuring there is no physical interference between them. Instead of full collaboration, mixed autonomy could be used in cases in which some complex decisions have to be made at execution time, for instance because of an unexpected fault, and control has to be given to the humans.

Large language models will open up new opportunities for research in planning. For instance, planning could be done from natural language requests from humans, instead of from formal descriptions of actions. More often, robots will interact with people who will interact with robots verbally.

This more complex framing of the planning problem means that we will need to develop more complex planners, capable of modeling and dealing with the uncertainty of humans. These planners will have to be safe, and deal with contingencies, adapting in real-time as the situation changes.

5.5.3 Manipulation and Full-Body Planning

More complex robots, capable of moving around the world and manipulating it at the same time, need more complex planning systems. More research is needed both in planning for manipulation (how to pick up things and do useful things with them) and in whole-body planning (how to plan for movements of the robot's body while manipulating the world). Traditionally, these aspects of the planning problem have been dealt with separately. Dealing with them together dramatically increases the complexity of the problem, and new techniques are needed to deal with this more complex framing of the problem. Not only are new algorithms needed, we must also integrate these algorithms with newly available hardware, such as GPUs.

5.6. Edge AI

Artificial Intelligence is seeing major progress in terms of delivering improved functionality for human-robot interaction, foundational models for navigation and manipulation etc. Many of these models are computationally demanding. To allow utilization on a broad range of applications it will be essential to make the methods available on the device rather than in the cloud. This implies that there are multiple research challenges that must be addressed:

1. **Energy Efficiency and Autonomy**: The energy constraints of robotic systems, particularly those operating in remote or autonomous environments, necessitate a focus on energy-efficient edge

AI solutions. Research should explore techniques such as model quantization, pruning, and compression to reduce the computational complexity of AI algorithms. Additionally, advancements in energy-aware hardware design, including low-power processors, energy-efficient sensors, and power management techniques, will be crucial for prolonging the operational autonomy of robotic systems.

2. **Real-time Processing and Latency Reduction**: Real-time decision-making is essential for enabling robots to respond quickly to dynamic environments and perform tasks with precision. Research efforts should focus on optimizing AI algorithms for low-latency execution on edge devices, leveraging techniques such as model parallelism, pipelining, and hardware acceleration. Additionally, edge computing architectures must be designed to minimize processing delays by colocating AI inference with data acquisition and actuation.

3. **Hardware-Software Co-design**: The synergy between hardware and software components is critical for maximizing the performance and efficiency of edge AI systems in robotics. Research should explore co-design methodologies that tailor hardware architectures to the specific computational requirements of AI algorithms used in robotic applications. This may involve developing specialized accelerators for tasks such as convolutional neural network (CNN) inference, recurrent neural network (RNN) processing, and sensor data fusion, integrated with efficient software frameworks for seamless deployment and management.

4. **Robust Perception and Situational Awareness**: Reliable perception systems are essential for enabling robots to interpret and navigate complex environments effectively. Research should focus on developing robust AI algorithms for sensor fusion, SLAM, object detection and tracking, semantic segmentation, and scene understanding. These algorithms must be designed to handle challenging scenarios such as varying lighting conditions, occlusions, cluttered environments, and sensor noise, thereby enhancing the situational awareness of robotic systems.

5. **Adaptability and Continual Learning**: The ability of robots to adapt and learn from their interactions with the environment is crucial for achieving long-term autonomy and versatility. Research should explore techniques for continual learning, where robots can incrementally acquire new skills, adapt their behavior to changing tasks and environments, and improve performance over time through experience. This may involve online reinforcement learning, meta-learning, transfer learning, and knowledge distillation approaches tailored to robotic applications.

6. **Privacy Preservation and Security**: Protecting the privacy and security of data processed by edge AI systems in robotic applications is paramount, particularly in scenarios involving human-robot interaction and sensitive information. Research should focus on developing robust encryption, authentication, and access control mechanisms to safeguard data integrity and privacy. Additionally, techniques for secure multi-party computation, federated learning, and differential privacy should be explored to enable collaborative AI without compromising security.

7. **Edge-Cloud Collaboration and Resource Management**: Optimizing the distribution of computational tasks between edge devices and cloud servers is essential for achieving scalability, efficiency, and reliability in distributed robotic systems. Research should explore techniques for dynamic workload partitioning, data offloading, and edge-cloud synchronization to balance resource utilization while minimizing latency, bandwidth, and energy consumption. This may involve developing decentralized orchestration algorithms, edge caching strategies, and adaptive communication protocols tailored to the requirements of robotic applications.

8. **Interoperability and Standardization**: Ensuring interoperability and compatibility between edge AI components and robotic platforms is essential for facilitating seamless integration and collaboration across diverse systems. Research efforts should include developing open standards, communication protocols, and software interfaces for exchanging data, commands, and services between edge devices and robots. This will simplify plug-and-play interoperability, interoperable software frameworks, and modular architectures that promote reusability, scalability, and flexibility in robotic systems.

Collaboration between researchers in AI, robotics, computer engineering, and related disciplines will be essential for developing innovative solutions that enable robots to operate autonomously, intelligently, and securely in real-world environments.

5.7. Machine Learning

Over the past decade and a half, deep learning has been used effectively to improve machine vision, thereby facilitating robotics perception. Furthermore, deep reinforcement learning has been used for robot control at various levels, from low-level motion control to high-level planning. Most recently, the explosion of foundation models has fueled advances in numerous areas of AI, and has fueled a great debate about the role of foundation models in the future of robotics. Because foundation models rely on massive datasets, a part of the AI community believes that once we have models trained on truly multimodal data resembling real robot experiences, robot control will emerge from such models.

This perspective relies on an analogy between how AI has advanced based on large language models (massive amounts of text) and how robotics may advance based on large multimodal models. However, the amount of data needed for robotics is difficult to comprehend: it would require at least massive amounts of video, audio, and tactile data from uncountable environments and points of view over different trajectories and time-series. How sufficient data of such scale could be economically acquired and stored is not clear. Consequently, part of the AI community believes that simulations may be a productive way of addressing that challenge. However, robotics has been a difficult domain for simulation; much like biological systems, which require evaluation in the real world (for example for drug design), robot behavior in the real world and interactions with humans have not yet been effectively simulated. Simulation is used in robot development, but most practitioners acknowledge that real-world trials often contain large surprises and much additional work.

Foundation models hold significant promise for robotics, in several areas. First, they enable robots to communicate with users verbally, creating a new and natural mode of interaction. Second, they enable language-based robot training, which can be combined with visual demonstration and significantly advance robot learning from demonstration (LfD). Early work has already made advances in these areas. Therefore, there is no doubt to the value of building large multimodal models for robotics, with the understanding that these will not address all areas of robotics.

While large datasets for robotics do not yet exist and there are difficulties of simulation as described above, efforts towards collecting real-world robotics as part of the National Artificial Intelligence Research Resource (NAIRR) could benefit robotics, which is physically embodied AI. The proposed NAIRR, currently starting as a pilot program run by the National Science Foundation, has a goal of providing computation resources and datasets to advance the ability of researchers, educators and students to have access to high-quality resources that are too expensive to replicate on one's own. However, the robotics community has not been sufficiently represented in this planning, which is a threat to robotics – as well as AI – in the US.

When robotics systems use machine learning, particularly deep learning, it can be difficult – if not impossible – to know what the system will do in all situations and to know why the system acted in a particular way. Without the ability to provide people with an understanding of a system, systems may not be trusted, which can lead to misuse or disuse. Research in explainable AI and interpretability is looking to fill this gap, with similar efforts occurring in robotics.

The performance of a complete autonomous system is more than the sum of the performance of its parts. Learned components of complete autonomous systems must be evaluated in terms of how they affect the entire system's performance. At the same time, evaluation of a complete system is a time-consuming and possibly laborious process. For example, autonomous driving companies extensively test their hardware and software stacks by driving millions of miles under a range of scenarios. As we call for more research into building complete autonomous systems, we also must improve how we can efficiently and effectively evaluate these systems. To achieve these goals, we could develop active testing methods for evaluation of autonomous behaviors, (e.g., automatically identifying test scenarios or behaviors that provide a reliable assessment of a complete system), create methods for evaluating systems using logged data from previous runs of the system (e.g., evaluating counterfactuals in causal inference or off-policy evaluation from reinforcement learning), or find scalable techniques for formal verification of complete systems in hard to model environments.

5.8. Human Interaction

5.8.1 Collaborative robots (physical human-robot interaction)

A collaborative robot is one that works alongside humans in a shared workspace to enable a task with improved speed, accuracy, strength, or scale compared to what a human can do alone. Unlike traditional industrial robots, which typically operate in isolated environments behind safety barriers, collaborative robots should interact safely and directly with humans. New developments are needed to make safe, flexible, compact, and easy-to-use collaborative robots.

Safety: Safety can be achieved through the design of the physical embodiment of the robot or through software techniques that prevent harm to human users. Robot designs with low inertial mass and/or compliant surfaces can prevent physical harm to humans in the same workspace. However, a key challenge is enabling sufficient strength to achieve the task at hand (e.g. moving a table) while also being "soft" enough to avoid danger during inadvertent or purposeful contact with a human. This requires research into new materials, including variable stiffness actuators and surfaces, lightweight deployable and shape-controlled structures, and smart materials that integrate actuation with structure. In software, safety rated and certifiable human detection are needed to ensure that a robot is not commanded to physically overlap with the human body. Interpretability of autonomous robots is also necessary for humans to act safely as well as feel safe, which is related to explainability as described in the Machine Learning section.

Flexibility: Collaborative robots should quickly adapt to new tasks and/or differing actions of the human collaborator. Learning from demonstration (or imitation learning) has emerged as a promising method to teach robots to perform autonomous tasks with relatively little data (compared to some other learning methods), and expanding these approaches to tasks that involve humans and collaborative robots might be an efficient way of enabling collaboration. Adapting to user preferences over time, through various versions of reinforcement learning, has also been shown to be highly effective in creating human-centered systems.

Some interaction contexts involve modeling the user, including models of user perception, task-related actions and goals, as well as preferences. Such models can be general, for contexts where multiple users interact with the robot on the same task(s) (e.g., sentry robots), or highly individualized when the interaction is very specific (e.g., physically or socially assistive interactions).

Compactness: Robots that work in the same physical space as humans should be as compact as possible to maximize human freedom of movement while avoiding collisions. Similar to the materials- and structure-based opportunities described to enable safety, new developments in smart materials and actuators can enable robots that take up minimal volume within the human workspace. As explained in the Embodiment section, novel designs that take advantage of mechanical interactions to change their pose or shape with minimal actuation.

Ease of Use: Humans must be able to seamlessly interact with all robots. In the context of collaborative robotics, this must be achieved with a focus on task achievement. Modes of interaction that are task-focused include allowing the human to ask the robot for help, as well as allowing the robot to ask the human for help in deciding when, how, and why to achieve a collaborative task. We also require methods for collaborative robots to convey their capabilities and limitations to a user, in a seamless manner akin to the 0-Learning Curve described in a previous section. Moreover, the interpretability described for safety is also important for ease of use, and this area of research is described in the Machine Learning section.

Applications of collaborative robotics that require substantial additional research include mobile manipulators in the home, human caring tasks, and dynamic tasks, such as collaborative tool handling, joint manipulation of objects, etc.

More generally, future deployment of collaborative robots requires the establishment of standards for safety and legal frameworks.

5.8.2 Social companion robots (social human-robot interaction)

The potential for companion robots in numerous areas of human work and life is vast. Section 3.4 discussed their potential for supporting the aging population, but they are equally relevant to and prototypes have already been explored for infant movement development, early child development, K-12 STEM education, autism therapy, stroke rehabilitation therapy, mental health support, and many others. Work to date has been limited in part by the robots' abilities to verbally interact with users, some of which have been significantly advanced by natural language processing via foundation models.

While the robots' ability to engage in dialog is becoming increasingly within reach, making it generally robust and accessible is still far away. Users with accents, speech disfluency, or speaking languages models are not trained on are not yet supported. Next, in the robotics domain, language must be unambiguously situated in the physical world, allowing the robot to understand the user's intention when pointing while speaking, or leaning their head or body when indicating; analogously, the robot should be able to communicate equally fluidly through not only words but also back-channels: head and body pose, facial expressions (if it has a face), hand and arm gestures and movements, etc. This multimodal communication is critical for all types of interaction, from the physical to the social.

Another major challenge in any type of human-robot interaction is user understanding: the need for the robot to perceive, infer, and understand the user's state, behavior, intentions, and goals. While foundation models are expected to advance this area of robotics, they are unlikely to have sufficiently broad training data for all domains and contexts of human-robot interaction, and are furthermore highly likely to have biased data. For example, if models are not trained on data involving users with particular types of physical differences or disabilities, they will not be able to properly understand, reason about, and respond to users from those groups. This can be a serious barrier to advancement in medical and rehabilitation robotics. The same idea can be applied to a broad range of domains for assistive and companion robots, including users with autism, stroke survivors, users who stutter, users in wheelchairs, etc.

Companion robots will also benefit from research in affective computing, which focuses on understanding the user's affective/emotional state. However, unlike other computational contexts, human-robot interaction requires models that enable robots to understand human affect to operate in a tremendous variety of environments (including different points of view, lighting conditions, motion, occlusions, etc.).

The embodiment presents additional challenges for perception: if the robot has humanoid or zoomorphic form, with visual perception located on the head, then users will expect the head to be used affective, believable motion, at times taking the robot's focus of attention away from the user in order to behavior in socially appropriate and expected ways. Research into embedding perception into various robot embodiments in a way that is acceptable (and not "creepy") to users while providing functional value toward safety and efficacy is an open area of research.

More generally, physical design of robot companions is an unexplored area that will require collaboration of multiple disciplines, including social science, usability, and robotics as it will need to address a considerable space of constraints, including safety, cost, efficacy, cultural appropriateness, adoption, and more. This area of research will need to address the problem of combining physically and socially assistive robots, a new area of research. Physically assistive systems are currently designed purely for physical function, and lack social engagement and appeal, thereby lowering adoption and efficacy. Social features must be added based not only on user preferences and cultural norms, but in ways that do not interfere with physical form and function, as well as cost and safety. Some researchers believe that humanoid robots may be the answer to the challenge of general functional form, but such embodiments are complex and expensive and may not be the most effective and affordable choice for a wide variety of specific use cases, especially in homes. Therefore, research and analysis is needed to better understand the interplay between robot from and function for various contexts of real-world deployment, ranging from public to private environments, single-user vs. multi-user, high stakes (time-sensitive, related to sensitive data e.g., health, etc.) or not (information and object retrieval, entertainment),

5.8.3 Mediated interaction

While collaborative and social robots usually operate in the same space with their users, some robots allow us to project ourselves into remote environments or use robotics devices to extend human capability. In some cases, those environments are at some distance from the user, with robots used as a tool for telepresence, i.e., the robot is at a different scale or enables access in difficult-to-reach locations, such as in teleoperated surgery, inspection of pipes, bridges, and other infrastructure, and in space (Moon, Mars, etc.). In others, the remote environment is dangerous, as would be seen after a natural disaster with a collapsed building. Prostheses to replace missing limbs are also a form of mediated interaction, where the teleoperated robot is physically attached to the user's body. Interaction can be mediated through various methods, ranging from joysticks to voice commands to implanted brain-machine interfaces.

One difficulty of these types of interfaces is providing the user with sufficient situational awareness of the environment around the robot to allow the robot's operator to make correct decisions for the robot's control. If not well-designed, interfaces for mediated interaction can create a high workload for the operator – and could place them at risk when they are unable to pay attention to their surroundings. Virtual reality systems can provide additional information about the remote environment, but further cut off an operator from their environment. Augmented and mixed reality technologies have the potential to improve situational awareness when line-of-sight is possible, with new consumer technologies for wearable extended reality experiences providing an opportunity for fast integration of new situational awareness technologies. There is a need to create situational awareness tools with application-appropriate levels of immersion in the robot-mediated task versus the user's local awareness of their own environment.

Haptic (touch) feedback is also critical for certain robot-mediated tasks – both for accomplishing physical tasks and supporting social interactions. In scenarios where touch-based exploration is required to identify mechanical properties of the environment, or when dexterous manipulation is required to achieve a task but visual information is occluded or limited, haptic feedback to the human operator enables precise, efficient manipulation. This requires improved technology for sensing distributed contacts with the environment in a manner that covers a large area of the robot body while being low-profile with efficient packaging. It also requires that haptic devices that stimulate the human user be more wearable than previous generations of desktop haptic devices – they need to be lightweight, comfortable, and portable while still providing salient feedback to the user. Interpretation of haptic information should have zero learning curve (as described in Section 4.3), so the feedback must be natural and intuitive. New design and fabrication techniques borrowed from soft robotics should be developed to enable improved wearable haptics.

A form of mediated interaction relevant to security and safety scenarios is where a human operator controls non-anthropomorphic robots, or robots that do not match the kinematics of the human body. For example, to go beyond a one human-one robot mediated interaction, a single human operator could potentially have different levels of control over swarms of robots through novel interfaces and multi-robot planning systems. Another example is a human operator controlling a continuum surgical robot that snakes through the human body in a minimally invasive fashion. Current surgical robots are commanded at the end-effector (i.e., the instrument tip), but continuum robots can control their entire sinuous shape, and current interfaces do not have an intuitive mapping between human input and the shape of such a robot.

6. Adapting Workforce Training for the Age of Robotics and AI

6.1. Introduction

The integration of robotics and AI into various industries is not just imminent—it is already underway. As these technologies streamline operations in sectors such as manufacturing, healthcare, logistics, and services, they also demand new skills from workers. Educational institutions and businesses must adapt their training programs to equip new entrants and current employees with the necessary competencies to thrive in this new environment. We briefly explore how trade schools, colleges, and workplace retraining initiatives can evolve to meet these demands.

6.2. The Need for Specialized Training in Robotics and AI

Robotics and AI are at the forefront of the fourth industrial revolution, automating complex tasks and making data-driven decisions faster than ever before. The need for specialized knowledge in programming, machine learning, mechanical engineering, and system integration is becoming critical.

Despite technological advancements, there is a significant gap between the skills needed to operate and maintain new technologies and the skills possessed by the current and upcoming workforce. This gap poses a threat to productivity and innovation, highlighting the urgent need for updated educational models.

6.3. Trade Schools: Specializing in Practical Skills

Trade schools are uniquely positioned to adapt quickly to industry demands and can provide specialized, practical training that is directly applicable to jobs in robotics and AI.

- Develop Cutting-Edge Programs: Trade schools can introduce cutting-edge programs that focus on robotics maintenance, AI systems management, and automation technology. These programs should be designed to meet the immediate needs of local and global industries, ensuring students gain relevant and highly sought-after skills.

- Emphasize Soft Skills in Technical Training: While technical skills are crucial, soft skills such as problem-solving, teamwork, and communication are equally important in managing and working alongside AI systems. Integrating these into robotics and AI programs can enhance employability and effectiveness in the workplace.

- State-of-the-Art Facilities: Investing in state-of-the-art facilities, such as labs equipped with the latest robotics technology and software, will provide students with hands-on experience that simulates real-world scenarios, preparing them for immediate entry into the workforce. Providing access to such facilities is unreachable for most trade schools today, and there is a need to consider creative financial models.

6.4. Colleges and Universities: Fostering Interdisciplinary Expertise and Research

Higher education institutions can leverage their resources to offer more theoretical and research-oriented education in robotics and AI, which is crucial for pushing the boundaries of what these technologies can achieve.

- Interdisciplinary Degrees: Colleges can offer degrees that combine AI and robotics with other disciplines like ethics, psychology, and business. This approach prepares students to understand and tackle the complex issues that arise from AI technology in society and industry.
- Expand Research Opportunities: Universities should expand their research opportunities, encouraging students to engage in projects that address both the technical and societal implications of robotics and AI. This might include partnerships with industry leaders to solve real-world problems or developing proprietary innovations that can be commercialized.
- Global Research Networks: By creating or joining global research networks, universities can enhance their educational offerings and keep both faculty and students on the cutting edge of technological advancements. Such networks can facilitate international collaborations and exchanges that enrich the learning experience and foster innovation.

6.5. Workplace Training: Ensuring Current Employees Remain Competitive

For businesses, investing in the ongoing education of existing employees is critical to maintaining a competitive edge. This can be achieved through several focused initiatives.

- Tailored Upskilling Programs: Companies can develop tailored upskilling programs that address specific skills gaps within their workforce. These programs should be designed with flexibility in mind, allowing employees to learn at their own pace without compromising their work responsibilities.
- Microcredentials and Certifications: Offering or subsidizing opportunities for employees to earn microcredentials or certifications in specialized areas of AI and robotics can enhance their skills and also serve as motivational tools.
- Leveraging AI for Training: Employers can also use AI technologies to enhance training programs. For example, personalized learning platforms powered by AI can adapt to the individual learning style and pace of each employee, improving the efficiency and effectiveness of training programs.

6.6. Public-Private Partnerships: Enhancing Training Accessibility

Collaborations between educational institutions, government entities, and private businesses can be instrumental in scaling training initiatives to meet large-scale needs.

- Government Subsidies and Incentives: Public-private partnerships can lobby for government subsidies and incentives that reduce the cost of training programs, making them more accessible to a broader audience.
- Community-Based Training Initiatives: By partnering with local communities and educational institutions, businesses can help develop community-based training initiatives that prepare local populations for jobs in robotics and AI, thereby contributing to local economies.
- Standardized Skills Framework: Developing a standardized skills framework through public-private partnerships can help align educational outcomes with industry needs, ensuring that workforce training in robotics and AI meets the high standards required by employers.

By strategically focusing on these areas, educational institutions and employers can not only enhance the skills of their students and employees but also contribute to the broader goal of preparing society for a future where robotics and AI play a central role. This will not only help mitigate the challenges posed by technological disruptions but also capitalize on the immense opportunities they bring.

7. Societal Considerations

Deploying robotics systems into society over the next decade raises numerous key societal considerations. Indeed, the growth and success of the robotics sector depend in part on social acceptance of robots in places where we work and live. Ensuring ethical application, fostering inclusion, guaranteeing safety and security, and encouraging entrepreneurship are paramount aspects of a robotics roadmap.

7.1. Ethics

- **Decision-Making Integrity:** Ensuring robotics and AI systems make decisions in a fair and unbiased manner is critical, especially in sectors like healthcare, and transportation services. Developing ethical guidelines and standards for algorithms will help maintain integrity in automated decisions.
- **Consent and Privacy:** New systems often depend on large datasets, which can include sensitive personal information. It is vital to implement strict guidelines on data consent, use, and storage, ensuring privacy is protected as per the highest standards.
- **Accountability**: There should be clear lines of accountability when it comes to AI actions. When an AI system makes a mistake, it must be possible to trace the decision back to the entity (or entities) responsible for its deployment and maintenance.

7.2. Inclusion

- **Accessibility**: Robotics and AI should be accessible to all, including those with disabilities. This requires thoughtful design that accommodates a wide range of physical and cognitive abilities.

- **Preventing the Widening of the Digital Divide**: There's a risk that the benefits of AI and robotics are disproportionately available to those with better resources. Ensuring equitable access to this technology, and its benefits, is crucial in preventing the widening of existing societal gaps.

- **Representation** in AI Development: Diverse teams can help prevent unconscious biases in AI systems. Efforts need to be made to include a broad spectrum of voices and backgrounds in the development stages of AI and robotics.

7.3. Safety

- **Physical Safety**: As robots take on more autonomous roles, ensuring they can operate safely around humans without causing harm is crucial. This includes rigorous testing and robust safety protocols. There are established standards in place for industrial robotics such as ISO 10218/R15.06, ISO/TS 15066, and R.15.08, but for more general use-cases there is a significant need for up-to-date standards
- **Weaponization**: No longer limited to science fiction movies and television shows, the weaponization of commercial off-the-shelf robots, assembled ad hoc by those seeking viral video fame from such stunts, is an unfortunate increasing phenomenon. While still rare, such incidents

greatly undermine trust and damage the image of all who work in the robotics field. Public policy should be developed to proscribe this type of misuse and to establish frameworks for socially acceptable use of commercial robotic technologies. Distinctions should be articulated between robotic systems designed, tested, and validated for use by defense agencies in weaponized applications, and those that are for general purpose use. The enhanced robot capabilities that will derive from AI innovations makes this issue more urgent.

- **Psychological Impact**: The impact of AI and robots on human psychology, including effects on children's development, mental health, and societal norms, must be studied and managed carefully.
- **Reliability and Fail-Safes:** AI systems and robotics must be reliable and equipped with fail-safe mechanisms that kick in if something goes wrong to prevent harm to humans or property.

7.4. Security

- **Cybersecurity Risks**: As more devices are connected and more systems are automated, the potential for cybersecurity threats increases. Securing AI and robotics from hackers and ensuring that these technologies cannot be used maliciously are critical challenges. Security risks potentially posed by robotic systems that are designed and manufactured in foreign adversary nations should be studied and potentially addressed by security standards or government policy.
- **Surveillance and Data Abuse**: The potential for AI to be used for invasive surveillance needs to be regulated. Policies and laws will be crucial to define and limit how AI can be used in monitoring and recording activities.
- **Autonomous Weaponry:** The development and use of AI in autonomous weapons need strict international regulation to prevent potential misuse and ensure global security.

7.5. Civil Rights

- **Law Enforcement**: The beneficial use of robotics in law enforcement has a long history, particularly in the field of explosives ordnance disposal. However, agencies adopting newer technologies have generated concern and even controversy. At the same time, these technologies have been used recently for demonstrably beneficial operations protecting officers, suspects and the public. Potential policy frameworks or best practices for the governance of advanced robotics in law enforcement should be explored and developed by an informed governmental process and socialized through federal law enforcement agencies and partnership channels. This would ensure comfort to communities and also encourage broader use in life-saving applications.
- **Surveillance and Privacy**: Increasing access to robotic technologies may raise concerns that citizens are using these devices to surveil each other or to invade personal privacy, at a distance or via autonomous mobility. Although topics such as facial recognition are active in policy development elsewhere, the impact of advanced mobile robotics on these societal concerns should be studied.

7.6. Entrepreneurship

- **Fostering Innovation**: Creating supportive environments for startups in AI and robotics can drive innovation. This includes financial incentives, intellectual property rights protection, and fostering incubator programs.
- **Ethical Entrepreneurship**: Encouraging startups to adopt ethical practices from the outset can help ensure that new technologies are developed and deployed responsibly.
- **Global Market Access**: Helping startups scale globally is essential for the widespread benefits of innovations in AI and robotics. This means reducing barriers to international markets and supporting cross-border collaborations and partnerships.

Broader Impact

Addressing these considerations requires a multidisciplinary approach involving ethicists, technologists, industry, policymakers, and the public. It also necessitates international cooperation to set global standards and norms for the development and deployment of AI and robotics technologies. This will ensure that as these technologies advance, they do so in a manner that aligns with the broader societal values and benefits humanity as a whole, and that the technologies are socially accepted.

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