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The State of Industrial Robotics: Emerging Technologies, Challenges, and Key Research Directions

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Executive Summary

In the past decade, European countries and companies—Germany and German companies, in particular—have been working to gain a competitive advantage in manufacturing by integrating the latest robots and related technologies into their manufacturing processes. For example, collaborative robots (cobots) that can work more directly with workers—rather than being separated by cages for safety reasons—offer a possible means to improve productivity without significantly lowering employment. However, the success and extent of efforts to update European factories have been relatively halting and uneven for a variety of reasons.

First, using these new technologies requires a significant rethinking about the nature and use of robots, as well as the clearing of technical and economic hurdles. Traditional industrial robotics technologies have primarily been used for highly repetitive manufacturing tasks that are not typically modified throughout the lifespan of a manufacturing line, and that can be performed reliably without human intervention. This is, in part, because traditional industrial robots are relatively inflexible, requiring extensive design and programming effort for integration into manufacturing lines. Integrators, which are companies that perform this integration process, are often required in order to make even small updates to manufacturing lines, resulting in technology integration processes that can be time- and capital-intensive. Also, robot programming interfaces and communication protocols are not currently standardized, and this—along with robot hardware and specifications that differ between companies—adds to the integration challenges. Each different system requires different knowledge and expertise for use in conjunction with other technologies. Thus, industrial robots are often only economically viable for high-volume production that takes place in large manufacturing firms, and

make less economic sense for small and medium-sized enterprises (SMEs) that focus on high-variety, low-volume production.

Second, the latest technology itself still may have limitations. Lightweight or collaborative robots (cobots) can be too slow or payload-limited to make sense for some industrial applications. Robot programming interfaces are also often difficult to use and require extensive programming knowledge, which limits the ability of line workers to easily repurpose robots for improving efficiency or to meet changing demands in manufacturing processes. Also, new and emerging technologies and software still cannot accomplish some key tasks. For example, robots are still far less capable than humans in operations that involve gripping objects, such as bin-picking processes, and the sensing systems that robots use to perceive the environment around them are still limited in the robustness they can achieve in factory settings. In other ways, the newest technologies may offer too much capability. They provide reams of information but extracting meaningful information from the large amounts of data that can be collected, and demonstrating tangible benefit from collecting such data, is another challenge that has limited the investment and use of the Internet-of-Things (IoT) and cloud systems.

Interestingly, worker resistance has not seemed to play a big role in slowing adoption of new technologies, partly because of worker protections in Europe that limit layoffs and partly because the top companies have recognized that involving workers in decisions on how to redesign manufacturing lines results in both better technical decisions (drawing on the workers' knowledge) and greater acceptance of new technology.

In this report, we detail findings from our interviews with robot manufacturers, original equipment manufacturers (OEMs) using robotics technologies, and industrial research institutions in Europe. We expand on the above points and provide recommendations for future areas of focus for industrial robotics.

Introduction

The field of industrial robotics encompasses the study, design, and use of robot systems for manufacturing[1] and how to integrate them into production lines. The field has been undergoing steady advancements in the past few decades. However, in recent years, Industry 4.0—a megatrend aimed at transforming automation—has promised to catalyze significant changes in the capabilities and design of industrial robotics.

Termed the fourth industrial revolution, Industry 4.0 can influence value and supply chains for many industries by providing a framework for digitizing manufacturing and fusing new and traditional technologies.

Banking on emerging technologies and pushed ahead by breakthroughs in information technology and smart communication, it promises to give rise to what researchers refer to as "the smart factory"—a factory that would combine physical and virtual infrastructures, and seamlessly employ collaborative robotics, smart computing, and digital networking using the Internet of Things (IoT) and big data to create intelligent value chains and optimize production.

We investigated the extent to which the robotics ecosystem has been transformed by Industry 4.0. In this report, we share the industry insights we gleaned and describe the challenges involved in moving toward Industry 4.0. We then provide research recommendations and a comprehensive overview of what lies ahead.

WHAT ARE INDUSTRIAL ROBOTS?

Industrial robots are—according to the International Federation of Robotics[2]—"automatically controlled, reprogrammable multipurpose manipulators programmable in three or more axes," where axes refer to the number of moveable joints. They are designed to handle specific automation applications within manufacturing companies, such as picking and placing objects; assembling and packaging; ironing, cutting, or welding; and product inspection, among others. These robots have traditionally been programmed to meet the specific needs of factories or companies that deploy them. Many of them are tailored to perform "dull, dirty, or dangerous" actions in lieu of a human worker.

Classic industrial robots are large, bulky automated machines that typically perform repeatable, routine chores inside a cage. In recent years, collaborative robots, which in industrial contexts are designed to safely interact with human workers in factory environments without the need for enclosures, have begun to emerge as potentially more lightweight, algorithmically capable, and affordable robotic solutions.

Collaborative robots can be equipped with sensors or other advanced visual technology for detecting humans. Ideally, they can be reprogrammed to perform new tasks and services. They are typically robotic arms.[1] While collaborative robots are not as widespread as the classic variety, these new and versatile systems promise to revolutionize business by allowing small companies to adopt automation at a lower cost.

INDUSTRY 4.0: A STRATEGIC PUSH FOR ADVANCED MANUFACTURING

In 2011, the German government coined the term "Industry 4.0" to describe a strategic vision for the advancement of manufacturing. The vision is to improve manufacturing by bridging digital and physical systems, and connecting classic and state-of-the-art technologies, products, and services in industrial environments. Industry 4.0 hinges on digitalization and communication, promoting an interconnected factory that can leverage real-time analytics of collected data to optimize production.

The framework and strategy, which first emerged as a result of the German government's acknowledgment of and reaction to the digitalization of manufacturing, aimed to spark a breakthrough in manufacturing innovation. With the hope that it could serve as an economic and technological driver for improving and streamlining the digitalization of manufacturing globally, Industry 4.0 was quickly adopted by other European countries and internationally.[3,4]

Germany led the charge with many German organizations partnering with those in developed and developing countries to ensure mutual readiness and a smooth transition toward Industry 4.0.[5] This created a push for the development of technologies that could further empower cyber-physical systems (CPS).

CPS are physical and engineered processes within a manufacturing operation that are monitored, coordinated, controlled, and integrated via a connected web of computer-based algorithms, communication, and networking technologies.[6] These systems are typically in “intensive connection with the surrounding physical world and its ongoing processes, providing and using, at the same time, data-accessing and data-processing services available on the internet.”[7]

CPS were and remain crucial to the implementation of Industry 4.0 since they are believed to lead to a higher level of operational efficiency, productivity, and interconnectedness within factories, resulting in increased production and, in turn, overall economic growth. Central to the framework that Germany created, and to CPS, are robotics and cutting-edge Internet of Things (IoT)-based connective technologies.

Study Aims

In this brief, we showcase reflections and insights from key European robotics companies and other related organizations in Germany, France, and Italy. Our selection included robotics manufacturers and integrators, original equipment manufacturers (OEMs) that use robotics technologies for manufacturing, and applied industrial research institutions, which are invested in research related to new technologies that are central to Industry 4.0 and which we interviewed as part of our research.

We looked at what questions manufacturers grappled with; what emerging technologies they experimented with; the different forms of interaction that they adopted, or were hoping to adopt, to make their robots more flexible and mobile; the extent to which collaboration between human and machine workers has been feasible in their factory and research environments; and, finally, what some of their requirements for application of certain advanced technologies and scenarios were.

The main aim of our research was to take a step back and survey state-of-the-art industrial and collaborative robotics as well as IoT-based connective technologies in use in these companies in order to evaluate the extent to which the use of these technologies has evolved over the last 10 years (since the introduction of Industry 4.0), what the primary drivers of innovations were, what bottlenecks companies faced in introducing new technologies, and what challenges and next directions companies are considering for the future.

We explored many facets of these topics: What drove shifts toward automation? What are some of the measurable improvements in productivity, efficiency, or quality that resulted from these shifts? What are some of the metrics that these companies used to evaluate the value of robotics integration? What are some of the greatest challenges they’ve faced, and how did they adapt certain technologies to meet their requirements? What are some of the unresolved problems regarding robotics integration, and how can the robotics industry and researchers work in partnership to solve them?

Additionally, we investigated the process of introducing robotics and related technologies—such as safety systems, sensing and perception mechanisms, deep learning, virtual and augmented reality, and cloud computing—into manufacturing processes and production lines. We also asked the companies about their initial expectations, lingering concerns, obstacles faced when integrating robotics systems and optimizing production, and some immediate future technological avenues they are exploring in robotics and IoT. One primary concern shared by many companies related to the high costs of integration of robotics technologies into manufacturing lines, even as the prices of the robots themselves are coming down. Companies expressed concerns about both the time and financial resources required for the integration process.

We also analyzed the impact of standardization, or the lack thereof, on the willingness of companies to adopt certain technologies. Standardization is the process of ensuring that both hardware and software used in an industry conform to a set of guidelines. Standards ensure consistency, uniformity, safety, interoperability, and compatibility across operations. Technology is always evolving. But we observed that the lack of design and security standards, for instance, have prevented many companies from fully experiencing the benefits of many new technologies or from justifying the risks of investment. The absence of unified programming languages, interfaces, or communication protocols for the hardware was a related challenge.

Interconnectivity of technologies made possible by IoT and cloud systems is still very limited, and bottlenecks related to sensing, perception, vision technologies, and gripping technologies still exist. Further, better data infrastructures and data-handling processes are needed in order to realize the full potential of the data collected via IoT-based technologies. This and other factors seemed to be critical to the adoption of automation.

The following pages detail some key insights from our research at greater length, interviews with industry players, and visits to manufacturing companies. Our full research, including methodology, observations, and proposals, can be read in our forthcoming paper to be published in *Foundations and Trends in Robotics*.

EVOLUTION OF ROBOTICS AND INDUSTRY

Today, numerous industries rely on robots and automation in manufacturing facilities. As the robots and the technologies managing their operation evolve, challenges arise in how to make robots safer, more adaptable, easier to use by less skilled workers, more responsive to the environment and the workers around them, more plugged into production cycles, and better integrated within manufacturing lines.

Advances and new inventions in this field are being made constantly, and many manufacturers hope to simplify, streamline, and reduce the costs of introducing automation and new robotic systems to both existing and new infrastructures. Aside from advancements in communication and information technologies that connect robots to the surrounding environment and to each other, researchers have been hard at work overcoming robots' limitations of function, speed, mobility, and flexibility.

But for industries to be able to absorb current, evolving, and future technologies—be it a lightweight robot arm or an automated guided vehicle—and weave them into bigger operations, the process must be smooth, economically viable, and cost-effective. The robot itself, and its functionality, is only one factor in this complex ecosystem.

THE PRICE OF INTEGRATION

Integration, in an industrial robotics context, is the process of introducing and merging robotics—hardware, peripherals, software, and supporting technology—into a production or manufacturing line to automate it. When companies decide to integrate robots into their manufacturing lines, they often have the goal of optimizing performance, saving money and time, and improving the quality of products.

In its simplest form, integration is the process of installing a robotic arm on a manufacturing line. The integration process involves programming the robot to perform a particular task, in response to external signaling mechanisms (e.g., a programmable logic controller (PLC), or a sensor detecting a part). In more advanced scenarios, integration can involve setting up multiple robots on a production line for a complex task, which can require multiple robots to act in concert with others on a large product (e.g., on the "body in white" process in automotive manufacturing). Many companies currently rely on external integrators, many of which are large robot manufacturers, to integrate automation and design workcells, which often include cages around the robots that define the parameters of their workspace.

While robot hardware has become significantly cheaper, the cost of the robot is a small fraction of the overall price tag of introducing automation to a manufacturing line. One large company, a well-known integrator of robotic and collaborative systems, put it simply: Robots are now inexpensive, but integration is not. Indeed, the integration process can be long, arduous, and expensive. There are the integrators who design the workcells and the engineers with extensive programming skills, which are required in order to make the robot perform the desired functions. Even small changes to a manufacturing line can require calling upon the integrators to redesign and repurpose robot workcells to meet the specifications of new tasks.

Both preliminary and maintenance costs can make integration of robotics prohibitively expensive for small- and medium-sized enterprises (SMEs). Therefore, robots that can be reconfigured, reprogrammed, and retasked are an added benefit to companies, so that their robots are reusable over time for different manufacturing processes and on different manufacturing lines.

Based on our extensive interviews and research, it is clear that companies are particularly concerned about integration costs as well as return on investment when deciding whether to purchase capital-intensive new technologies. Many companies cited the high costs of integration as a barrier to automation deployment. On the one hand, big manufacturers, employing large industrial robots, can get weighed down by attempting to integrate existing 15- to 20-year-old technologies and infrastructures with new and innovative robotics technologies on the same manufacturing line. On the other hand, SMEs, with production processes that run at a smaller scale, often find integration costs to be prohibitive or unjustifiable due to their smaller production lot sizes. This is because robots in the manufacturing context are currently primarily programmed to do specific tasks, and any change in the assembly process often requires reprogramming the robots or even an overhaul of the integrated manufacturing line.

Beyond these specific concerns about integration costs, decisions about whether to embrace automation predictably boiled down to other economic factors, such as the costs related to hardware acquisition and the time invested in setting up robots, transportation, programming, and taxes. In Europe, strong labor laws mitigating the risk of workers' displacement (where aging workers face a higher risk) because of automation also play a part. However, a number of companies we spoke with mentioned that they are experiencing labor shortages and are trying to develop new ways to automate, especially as a wave of retirement within their aging workforce is at hand. An aging workforce has also called focus on ergonomic needs, as more assistive forms of automation can reduce the risk of injuries from tasks that are routine and physically demanding.

While a number of companies mentioned that labor displacement calculations still play a role in their decision to automate, a few indicated that this metric is outdated, especially with the emergence of collaborative systems. Ergonomics, quality control, and reducing real estate occupied by robots were also important considerations for many of them, although perhaps secondary to cost calculation.

In deciding what to automate and how to integrate automated solutions, companies largely adopted one of two approaches: "top-down" approaches that favor fitting tasks to their existing automation capabilities, and "bottom-up" approaches that are open to innovation and the adoption of emerging automation capabilities to meet their industrial requirements. The latter enabled the adoption of more new technologies in recent years, and companies employing that strategy were generally more inventive and more creative in adapting these technologies to their needs.

The success and efficiency of a bottom-up approach seems to be tied to better integration with line workers, who typically have deeper knowledge of manufacturing processes and can judge the potential for innovation. With this approach, the line workers take a lead in identifying problems and challenges, pinpointing where the inefficiencies are and how tech can come in and provide a solution.

The top-down approach appeared to be outdated, since it entailed fixed assumptions about the role of technology in manufacturing tasks (e.g., robots placing parts with high precision in caged workcells, away from human workers). Employing a top-down approach can lead to missing the point of a new technology or failing to exploit its potential altogether. An example of this might include using a collaborative robot to perform a high-precision task behind a cage and away from human workers, while it can actually be used to work in closer proximity to humans and perform a wider variety of tasks.

Under either approach, manufacturing companies seemed particularly interested in adopting robotics technologies that have intuitive interfaces. Such interfaces can improve flexibility and decrease integration costs (specifically for complex or nonrepetitive tasks). This type of technology integration allows line workers who lack engineering or advanced programming expertise to operate or reprogram the machines.

THE VALUE OF WORKERS

Many of the companies we interviewed emphasized the importance of the roles and capacities of seasoned line workers who well know their production processes, including how these processes might be improved. Workers' perspective and voice appeared to be critical to the process of incorporating automation and collaborative robotics primarily across companies employing bottom-up mindsets, regardless of size. These companies largely focused on how to leverage the creativity of workers in conjunction with the use of new technologies instead of attempting to replace workers with these new technologies.

Several companies said they did not see a future where workers with deep knowledge of manufacturing processes were not part of the equation. A manufacturer specifically stated that "innovation stops with lights out factories." Another created a "Robot Experience Center (REC)" on the factory floor to allow engineers to work right next to manufacturing lines, where they could quickly communicate with line workers who had ideas about how to repurpose robots for different tasks.

An applied research institution that develops state-of-the-art technologies for industrial and service robots, and which interacts with several industry partners, reported that the "most impressive robot solutions" they had seen were those where factory workers were involved in commissioning a robotic solution through a co-creation process. In addition to the worker voice being critical to manufacturing innovation, some tasks such as moving materials between workcells, or cleaning machines, are more cost-effective when performed by humans.

Not involving workers in the technological design and integration process came with other drawbacks, too. In some companies, where line workers were not central to the introduction of new robotics solutions, workers often distrusted or disliked the robots. Additionally, companies noted that workers expressed fears that introducing new technologies would negatively impact workers' dynamics and social interactions, as well as lead to worker discomfort when working on a fast manufacturing line, or general discomfort related to the changes brought by the robot's presence.

Some workers were reportedly wary of their mistakes being tracked by sensor data from robotic systems, while others were thrown off by the pace that a robot-powered manufacturing line set. This is not uncommon; general distrust of robots was reported in several studies, including one that found that workers were likely to blame robots for workplace accidents if they were not personally operating and supervising the robot.[8]

In addition to relying on workers' expertise, some companies, such as a small manufacturer of lightweight robotic arms with a focus on innovative cloud technology and robot teaching methods, said that working with their clients, who are experts in their fields, is a critical piece of the technology development process. The small manufacturer of robots innovated "an app store for robots" open to both their industrial customers and the research community, a collaborative space where users could develop and share solutions specific to different tasks. Their aim was to enable rapid sharing of robotic solutions between the research community as well as companies working in similar fields, leading to more generalizable solutions.

COLLABORATIVE ROBOTICS AND INCREASED ACCESS TO ROBOTS

Introducing collaborative robotics, and related technologies, has the potential to improve human-robot cooperation and expand automation to improve production. One large OEM that we interviewed seemed keen on finding a delicate balance between maintaining standard industrial arms in proven-out parts of the operation and using state-of-the-art safe robotic arms for better and faster prototyping of automation solutions nearby assembly lines. Their goal was to be able to quickly integrate these solutions into their assembly processes once they were tested and proven to be of economic value.

Beyond production line optimization for big companies, the cheaper, lightweight, and easier-to-program robotic systems can also make robots more accessible to a broader range of companies and users. Classic industrial robots are, in large part, economically valuable to huge manufacturing enterprises whose processes involve repetitive tasks and production of large quantities of a single item, and in which a robot focuses on a single task and is usually difficult to repurpose. For economic reasons, large companies can justify investment in such machinery. They also have access to many engineers. SMEs, however, do not often have such capital or internal competence.

Emerging advancements in robotics, coupled with a push toward hardware and software standards, ease of programming, and more flexibility in robotics, could improve access to robots for manufacturing across the board, thus streamlining automation. One large robotics company noted that ease-of-use has the potential to dramatically change the landscape of collaborative robotics, since SMEs, if they can use the technology without relying on integrators or extensive internal programming expertise, will likely drive the market.

Closely tied to the idea of increasing access to robots is the idea of "programming the task and not the robot." Four different robotic manufacturers, ranging from large to small, discussed the idea of "empowering robots by empowering the people working with them" through easier-to-program robotic systems. These systems would enable workers to directly reprogram and repurpose robots to do new tasks that meet changing production needs without requiring the workers to have extensive programming expertise. Ease of programming allows for rapid integration and reintegration of robots and, in turn, quick repurposing—a goal that both manufacturers and the research community can work toward.

OTHER PROMINENT CONSIDERATIONS

Safety and standardization of new technologies were other issues that companies grappled with. The companies we talked to were additionally very interested in more robust security, improved sensing, more flexible technologies that are easily adaptable and reusable, and hardware that can communicate with a number of different cloud platforms.

Companies also highlighted the need for extensive reliability when introducing a new technology. Anomalies and variations (e.g., in lighting, which can affect robot perception) can bring the entire production to a stop. "The production world is so optimized that every minute that a robot is not moving is money out the window," a large manufacturer said. "This limits the uptake of emerging technologies within the manufacturing industry: While the technology itself is desirable, the longevity and robustness of that technology are unclear." We will expand on all these concerns in the following section, as we introduce the specific technologies that the companies discussed or had integrated.

While we do not make any policy recommendations in this brief, we would like to underline open questions about the technologies and hardware in use as well as highlight key research directions for the robotics community. We discuss how improving certain aspects of robotics and IoT-based technologies in industrial environments can enable faster integration and repurposing of these technologies in manufacturing lines as well as enhance connectivity between technologies in IoT-based systems.

We also demonstrate how efforts toward increased standardization of robotics technologies and technology development could be needed to increase flexibility and, in turn, encourage and incentivize the wide adoption and implementation of both factory-wide connectivity of automation and individual emerging robotics technologies.

DISCUSSION: FACTORY INFRASTRUCTURES AND EMERGING TECHNOLOGIES

The roles of both machines and humans in manufacturing have been evolving over the past decade—with emerging evidence in the research setting[9-12] suggesting that collaboration yields better results and smoother operations than with human workers and robots acting independently, or compared to "lights out" fully automated factories. Collaborative robots, which are designed to interact with humans in a shared space and close proximity, typically without safety fences, form the vision of an "ideal" future factory where robots and humans need not work in separation.

Furthermore, if widely adopted, IoT-based technologies are hoped to drive innovation to the next level by incorporating advanced computing and smart, reliable connectivity to connect products and services. For example, manufacturing tools and robots across an entire production line could communicate status information to a central database, which could then communicate commands back to each component, optimizing and adjusting production processes between all components in the line. Ideally, and because of IoT, robotics technologies will be able to talk to each other and the infrastructure surrounding them, further empowering collaborative robots, which can potentially transform classic production lines through assisting workers.

Industrial robots, which are widely used in managing supply and production chains, are autonomous machines that can take actions in the real world; they are robots that can rotate and move in different directions, and along several axes. They typically operate for long periods of time—up to 16,000 hours, with some products able to last for 80,000 hours—without failure. Industrial robotic arms, in particular, can last up to seven years. As previously mentioned, industrial robots are usually used by large and medium-sized companies. Industrial robots are typically larger and more expensive than new, lightweight collaborative robots, such as lightweight robot arms, which are smaller, more mobile, easier to integrate, and better able to adapt to different tasks through easier interfaces and programming.

Lighter, collaborative robots—current limitations notwithstanding—are cheaper, can move between tasks with more flexibility, and are generally more accessible. Most importantly, because of their capacity for reuse and repurposing, they are easier to integrate into manufacturing lines. Although they come with reduced payload capacities, the enhanced safety factor, the ease of use and programming, as well as the lower expenses attached to integration make lightweight the perfect vehicle for widening their use across different companies, large and small.

Figure 1. An automated robotic arm inside a factory workcell. The robot is within a cage to ensure the safety of humans in the vicinity.

Source: https://iowaengineer.com/robots-spatial-awareness/robot-pic

In our interviews, we were curious about how the companies—already invested in the development and integration of industrial robots—are receptive to new technologies that promote collaborative environments and IoT-style integration.

As we noted earlier, innovation in industrial robotics has followed different approaches. Some companies used collaborative robots in outdated ways, as they would have used classical industrial robots, while others chose to pivot and innovate; the two directions resulted in completely different experiences of emerging technology integration for these companies, which we will showcase as we expand on the technologies. Many of the established companies we interviewed valued systems that were less likely to disrupt existing infrastructures or require a complete overhaul of old hardware.

The following are some of the emerging technologies that small and medium manufacturers, as well as larger, more established companies, we interviewed have worked with or adopted within their factories, and how they engaged with some of the technical, design, and economic challenges that were attached with these technologies.

Safety systems are crucial to robots designed to work with or operate within a safe distance from human workers. Traditionally, cages around production cells where industrial robots operate have defined safety parameters to ensure that a human worker is not inadvertently harmed. But that means that a factory's real estate is used up by large cells to offer this kind of protection. New safety systems, such as passive systems that detect humans on contact, and active systems that use sensors to detect humans and avoid collisions with them can remove the need for cages altogether and free up space that can be utilized for other operations.

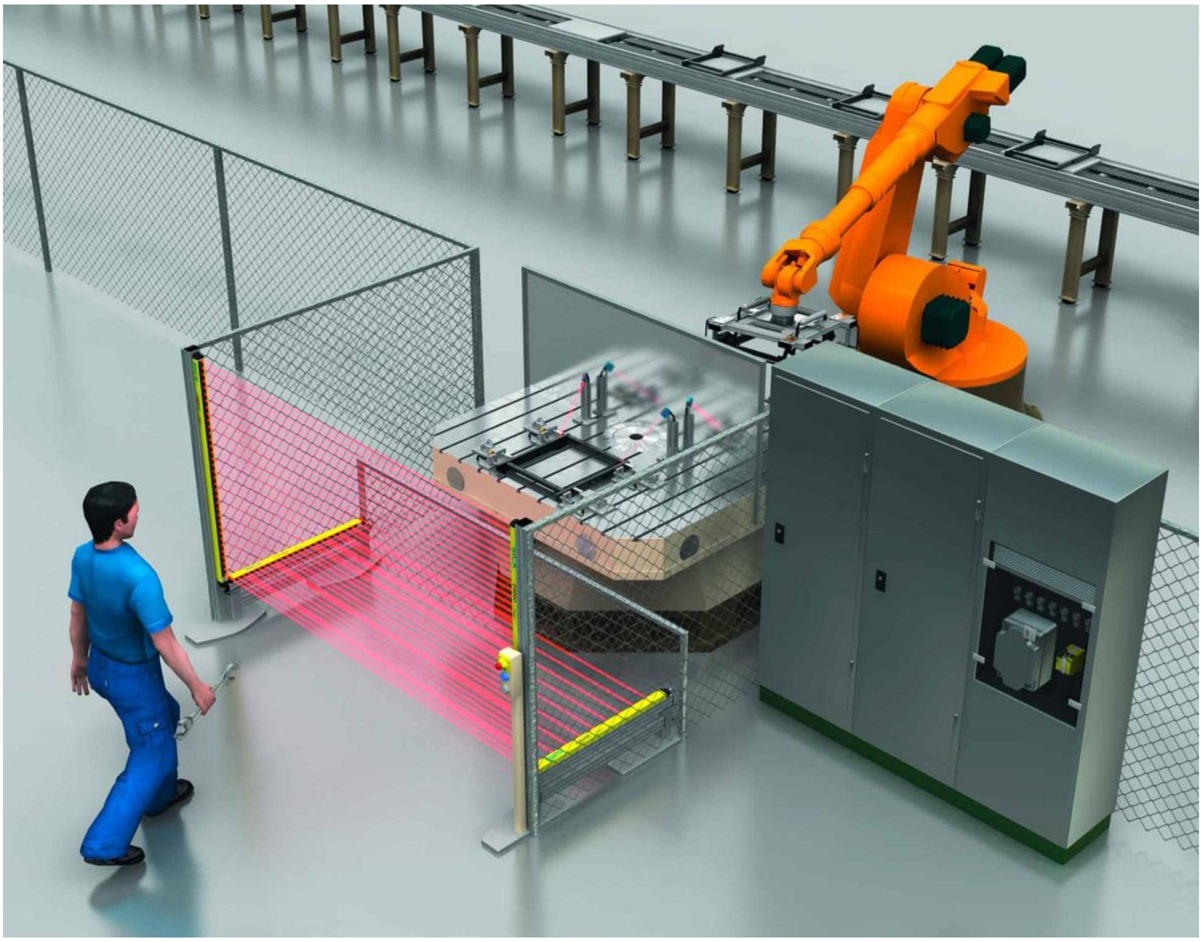
Some passive systems include skin sensors that trigger a stop when a robot collides with a human or an object within the environment. Some active systems involve the integration of sensors such as light or laser curtains that force a robot to power down if a human crosses them, or proximity sensors inside the cage where the robot operates to detect where a human is in relation to the robot, or capacitive skins that shroud the robot itself with a sensory film that identifies electrical field changes within a short range around the robot.

Irrespective of the safety system used, collaborative workcells typically require conformance to safety standards that limit a robot's overall velocity and the force with which a robot may interact with a person. As speeds are affected, companies debated whether there is enough benefit from applying these technologies to create shared workspaces and collaborative systems.

"Collaborative robotics is slow-motion robotics," commented one of the companies, a large OEM manufacturer producing a wide range of consumer products. The same company implied that reduced speed is a limitation that can needlessly complicate operations, while still acknowledging that the mindset regarding collaborative robots is changing, and that situations exist where robots are designed to assist human workers, improving their productivity rather than directly replacing them.

Traditional approaches, such as speed and payload limitations, are less applicable with new and emerging safety systems. For instance, smaller, payload-limited arms, conforming to safety standards, can have a limit on the amount of force they can apply. Alternative, emerging approaches to safety, however, focus on improving the design of the robotic arm itself to avoid collision with a human altogether. That's why more work geared toward improving relevant safety standards for collaborative robots is important.

Figure 2. An illustration of a safety light curtain, a fail-safe active safety system surrounding large robotic arms.



Source: *https://www.theengineer.co.uk/supplier-network/product/a-guide-to-safety-light-curtains/*

Collaborative and lightweight arms are examples of industrial robots around which human workers can safely operate.

Lightweight arms are small robotic arms that typically handle small payloads. Collaborative arms are arms that are designed to work in the vicinity of humans. The safety standards limiting speed and payload have meant that many collaborative arms so far have also been lightweight. Since lightweight arms are often slower, they are less likely to injure humans who bump into them given that the robot's task is also safe.

Lightweight robotic arms often implement compliance, which we discuss next. Compliance is a passive way to detect collisions, which allows the arm to deflect when encountering an unexpected obstacle. For example, if a compliant robot collides with a human, it will detect the collision and reduce the force it is applying, thereby reducing the potential for injury. Compliance is a reasonable approach to safety in this case, whereas it might not be with very large or very fast robots, which might injure a human upon the initial collision. The torque sensors within compliant robots allow them to react to the forces encountered in a manufacturing process, enabling them to perform tasks not amenable to a conventional robot. For example, a traditional robot cannot place bolts without damaging the workpiece, or without precise localization of the bolt and the bolt hole. A compliant arm is capable of accomplishing this task by adjusting its motion based on encountered forces during placement.

While lightweight or collaborative robots ideally free up space by eliminating the need for cages, their limited payload decreases their appeal. Since, for the most part, robots are not yet used in operations in which they can directly collaborate on the same workpiece as a human, some companies still prefer cages in lieu of collaborative systems because cages also stop humans from disrupting or slowing down the robot.

In addition, a large manufacturer noted that it's not only the robot that must be considered safe for human workers to interact with or work around, but the full system. Some tasks that robots perform, such as moving objects with sharp edges, are dangerous. In fact, many robots are designed to be used for tasks that are not safe for humans at all. This automatically limits the degree of collaboration between human workers and robotic workers and informs the design and scope of applied safety systems. One large robot manufacturer commented that "a robot is only as safe as the task it is performing."

Some collaborative scenarios—where the tasks that the robots performed were considered safe—were still viable. Those mainly involved the robot slowing down or stopping as a human associate collected completed parts from the workcell. As sensing and algorithmic capabilities of collaborative arms improve, companies hope to expand the use cases of these arms beyond how they are currently used.

Figure 3. A collaborative robotic arm that can safely work alongside humans.

Source: https://www.assemblymag.com/articles/91862-human-robot-collaboration-comes-of-age Photo courtesy of Universal Robots A/S.

Compliant arms utilize integrated torque sensors for improved interaction capabilities and can be used both for passive safety, detecting humans on collision, and for complex tasks.

Recent developments involved companies using these devices to perform complex tasks that require manipulation of loose-fitting parts. They have additionally been used as part of new, collaborative systems that, by design, enable safer close-proximity human-robot work. Although they are being used for some new tasks and for improved safety, reports on the use and uptake of compliant arms were mixed. The technology can overcome some limitations related to sensitive manipulations, but there are still some out-of-reach tasks. However, there seems to be agreement that they can be a valuable technology, but more development is needed for their full potential to be realized.

Robotic gripping in which robots can hold or pick up or manipulate objects is still far behind human gripping capabilities. A large robotic manufacturer we interviewed described physical gripping hardware as an enormous challenge. Advancements in the technology, and toward improving flexibility of the hardware, cited by companies and research institutions, provided some hope that the technology may benefit from emerging innovations such as deep learning or more robust sensing systems that can improve gripping performance. One large, multinational manufacturer of industrial electronics products has additionally used cheap additive manufacturing (AM) technologies to quickly and cheaply tailor grippers to parts.

Sensing and perception, data handling, and predictive maintenance are among the technologies whose potential and application are closely tied. Sensing, perception, and data handling, in particular, work together to improve both the robot's perception of the physical environment, other robots and human workers, as well as production processes. Advancement in one area, such as the usefulness of outfitting robots with sensors, is dependent on a strong data infrastructure for handling data for overall production to be significantly improved.

While sensing has, for instance, improved the capabilities of autonomous guided vehicles (AGVs) on factory floors through advanced perception algorithms, it has proved insufficient in other contexts, especially in terms of robustness, such as in contexts with large, high-speed industrial robots that need fast perception capabilities to ensure safety, according to an applied research institution focused on machine tools and automation.

Meanwhile, one primary use of the data that is currently collected by the companies we interviewed was predictive maintenance—the process of incorporating real-time data about a tool's condition for the purpose of scheduling maintenance procedures, consequently saving money and ensuring smooth performance. But companies want to generate more value from all the raw, big data that they collect. In other words, the amount of data harvested is huge, but the solutions that can utilize this data are few. A large robotic manufacturer referred to this problem as getting "smart data from big data."

While generating value in the form of usable information from raw data is difficult, information is the foundation of smart factories and is one of the key enablers of many emerging integrative technologies that depend primarily on interpreting and utilizing this data.

Improved programming and communication interfaces can enable humans with little programming experience to control robots to perform a variety of tasks, while communication interfaces enable robots to communicate with other hardware and software.

Beginning about a decade ago, robots that were marketed as being easy to program drew companies' attention to collaborative robotics. A decade later, for the majority of companies that we interviewed, the focus on ease of programming hasn't changed; adoption of collaborative robots is still accompanied with an increased focus on development and design of interfaces; the readiness to use these robots is tied to the ease of programming, prototyping, flexibility, and speed of integration.

While reports varied across companies of just how easy it is to program some collaborative robots, smaller companies, such as a startup we visited, grappled with the challenge by coming up with their own development solutions. For instance, they created platforms that enabled users to code using traditional languages such as Java and C++ or graphical programming languages that they developed in-house, making robot programming accessible to a broader range of practitioners. One of the enterprises we interviewed, a medium-sized company that manufactures small- to medium-payload industrial robots, explained that robots produced by different companies possess their own programming languages and communication protocols, with 17 to 20 different languages currently in use, most of which are proprietary. A large automotive manufacturer that produces a variety of luxury consumer vehicles said that the Robot Operating System (ROS) has emerged as one possible standard programming framework for industry. As with other technologies, the need for standardization in communication interfaces was highlighted here, too.

Autonomous guided vehicles (AGVs) are mobile service robots that are equipped with sensors and are able to navigate factory floors, on wheels, to move material and that can travel under their own control.[2, 13] Out of nine companies we interviewed, seven have been incorporating AGVs in some capacity or another, whether for production or demo services, or have plans for integrating them in the immediate future. While they are capable robots, powered by location-based and mapping algorithms, they are another form of technology hampered by the lack of standards. For instance, this lack stands in the way of employing intelligent fleet management, a form of management of manufacturing operations and production flows that is primarily dependent on connectivity, network services, and a layered data architecture that juggles storage and real-time data to predict factory floor logistics and to optimize scheduling of AGVs.[14] However, standards are emerging in other industries, such as the automotive industry, as one of the large manufacturers we interviewed pointed out, where a high demand exists for such systems.

Industrial Internet of Things (IoT), perhaps the quintessential requisite for full cloud-based technology integration, has not yet been fully adopted by companies and remains in a "pre-development stage." It is muddled by issues of privacy, questions over data ownership and autonomy, as well as security concerns. "People aren't ready to open their factory up to the internet or cloud," according to a medium-sized manufacturer of small- to medium-payload industrial robots. Since the realization of IoT relies on collection and transfer of data, a large robotics company also cited concerns about political problems in transferring information across national borders, as well as whether computation should be centralized in local computers or moved entirely to the cloud.

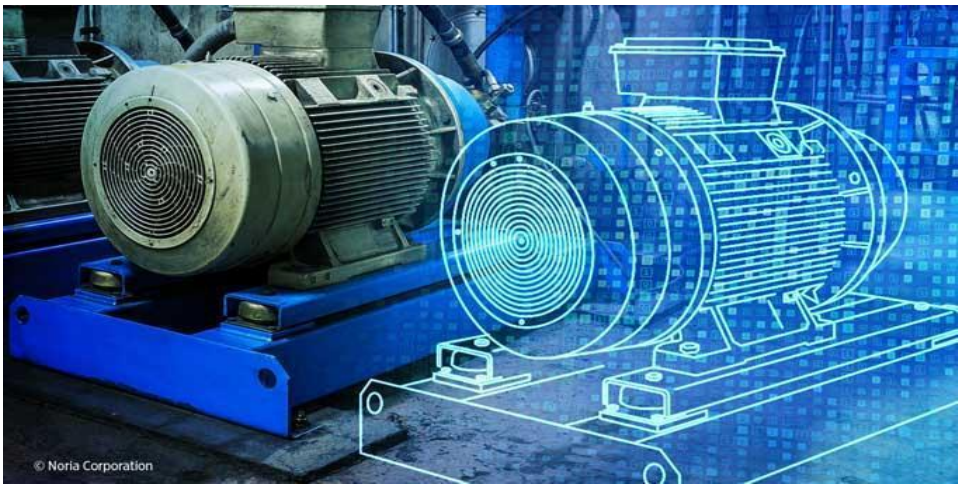
IoT is perhaps another example of how lack of standards coupled with limitation in data infrastructure can throttle complete integration of promising new technologies and disincentivize investment in them. Without a clear idea of what potential both IoT integration and data management in automation carry, and what the full benefits for the companies are (and whether these benefits justify the cost of investment), companies will understandably remain hesitant to throw money at the infrastructures that comprise IoT systems.

Simulation of robots or how they function within a value stream can save a manufacturer time and money, as it informs decisions about the best type of robot needed for a company's requirements in line with the robot's capacity. It can help pre-determine the viability of integration of certain robots into existing production lines; it allows a company to calculate the Economic Value Added (EVA) for different manufacturing setups, the cost of robotic solutions over the robots' entire lifetime; and it can also help users to study human-machine interfaces and to inform human-centered design processes. It has become an essential part of automation, at both the manufacturing plant and individual workcell level, so much so that one company described simulation as "our way of life," while a multinational consumer-oriented company described automation and simulation as "two sides of the same coin," adding that it may be too risky to automate in many cases without simulating their automation solutions first. One large manufacturer said it now possesses a 3D model of its entire manufacturing line.

Simulation, however, has been enhanced with innovations such as **digital twins**, which help companies create complete 3D environments—a facsimile of realistic factory conditions, **and augmented and virtual-reality systems**, which we discuss below. Simulations of robotic arm motion in isolation are different from that in a real-world, dynamic setting, where incidents like collisions, for instance, have to be accounted for. Therefore, enhanced simulation technologies, such as digital twins that can account for dynamic environmental factors, are of value. Companies have reportedly used digital twins, digital replicas of their factory environments, including systems, equipment, processes, etc., to validate line performance, simulate tool behaviors, and allow users to map components in their production lines and interactions between them.[15] A large, multinational manufacturer of consumer products, including power tools, reported using digital twins as an "enabling" technology that can support flexible automation by reducing integration times from multiple weeks to a few days and enable companies to quickly assess multiple possible integrated solutions.

Companies also expressed interest in virtual reality (VR), which can create immersive or semi-immersive 3D environments that mimic real-life conditions[16] and incorporate real-world physics. Augmented reality (AR), a form of human-machine interaction that overlays computer-generated information onto a real-world environment,[16] was also of interest to companies, albeit in a lesser capacity than VR. The challenge remains in developing higher-fidelity simulations, integrating multiple levels of abstraction, and improving computation so that the simulations can anticipate the challenges in complex environments and the effects of integration on the robot itself, and ultimately lead to better predictive maintenance. So far, certain environmental factors are not perfectly modeled, and the VR systems and simulations that we observed were only used in a preliminary capacity.

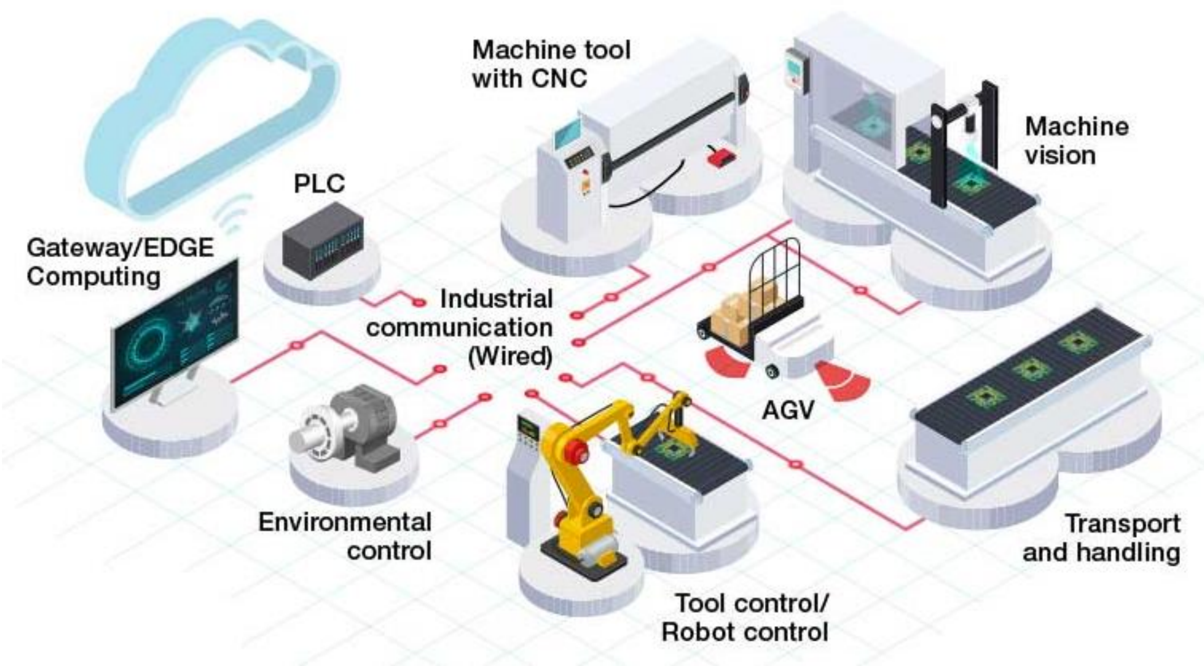
Figure 4. Digital twins, facsimiles of industrial assets, allow physical components to be represented in a digital environment. This is valuable as it can aid in simulation and in integration.



Source: https://www.reliableplant.com/Read/31897/digital-twins-ai

Cloud systems and computing resources over the internet are plagued by privacy and intellectual property concerns, and a lack of standardization for protocols to handle communications. IoT and cloud connectivity are pillars of Industry 4.0.[7] The large companies interviewed said they had to develop their own cloud platforms to be able to integrate all of their various technologies with them, often developing workaround solutions to cater to old hardware, while smaller companies relied on systems developed by larger ones, since they did not have the in-house expertise to develop their own platforms. Some manufacturers have reported using legacy systems that are either difficult to migrate to the cloud or cannot be connected at all. Reliability of communication through cloud systems also remains an issue.

Figure 5. An example of how IoT and cloud systems can be used to connect the components of and fully coordinate a production cell.



Source: https://www.electronicproducts.com/why-predictive-maintenance-is-fundamental-in-industry-4-0/#

Production control is a major vision of Industry 4.0 that involves cloud computing connecting factories in order to fully coordinate production. While it does not exist yet, as systems within factories are often disconnected with no easy path for integration into a unified framework (the "island problem"), this capacity would allow control and optimization of entire production lines across various infrastructures. It is seen by many companies as a current and future goal, the realization of which will remain dependent on enhanced data infrastructures, better data handling, and major improvements in cloud systems that would be in charge of "automating automation," as one company has put it.

Reflection: Summary of Challenges and Conclusion

We observed the following technical and design challenges that impact the ability of manufacturers to incorporate new collaborative and interactive technologies into their manufacturing processes. These considerations apply to manufacturers broadly, but they can be prohibitive for SMEs wishing to introduce new technologies.

- The absence of standardization in many aspects of robotics made it difficult for some companies to exploit the full potential of promising technologies or to incorporate new types of robots into manufacturing lines. Some companies developed home-grown systems and capabilities over the years that they would prefer to continue to use. Others, often smaller companies, are designing manufacturing lines or purchasing new technologies from the ground up. Each type of robot might require knowledge of different programming languages, interfaces, or communication protocols for use. Standardization should cover all of these considerations, besides safety standards and hardware. "Standardization is not as easy as one thinks," a large robotics company remarked in our interviews. "There are many experts to listen to. It must go hand-in-hand with which technologies are capable of what things and an understanding of the processes they're part of."
- The fact that current robotics technologies cannot always be quickly repurposed limited the potential use cases of robots as well as experienced line workers' ability to leverage their deep domain knowledge to improve manufacturing processes through direct repurposing of the robots. Flexibility was also considered important for increasing the applicability of robotics to different levels of production, including high-mix and low-volume production; faster integration and reintegration times; re-configurable workcells and manufacturing lines; reducing the factory footprint by allowing manufacturing of multiple products along a single line; and enabling the reusability of robots.[17]

While interconnectivity of technologies is considered essential for full IoT integration, security and privacy concerns over connecting factories to the cloud still exist, as well as issues related to reliability of communication through cloud computing systems, and how to organize and store data. To our knowledge, IoT and cloud systems are currently limited to information exchange between robots, and have not yet been extended to production optimization, or for achieving monitoring and centralized control, which several companies cite as a current or future goal of automation.

- Extreme robustness, faster integration, and removal of technological bottlenecks related to sensing, perception, and gripping are critical to encouraging investment in and the mass adoption of automation.
- As more manufacturing tools, workcells, and products carry sensing tools, large amounts of raw data are continuously collected. Many companies, however, find it difficult to extract usable information from this data, save for maintenance purposes. (We discuss this further in the next section.)
- Vision technologies, while promising for ensuring the safety of robots and reducing quality check costs, are still a long way from being optimal. The same challenges that apply to data and robustness of systems apply here. Our research shows that vision systems and corresponding

algorithms often performed well in research settings or other well-controlled settings, but they broke down, in different ways, in actual factories. Without rock-solid reliability, recent advancements in algorithms (such as deep learning-based architectures) are not robust enough to be used.

- Lightweight robots are inherently safer, by virtue of their reduced payload. In the event of a safety system failure, their "fail-safe" human safety implications are comparatively better than heftier industrial robots, which can be powerful enough to crush or seriously injure a human worker. But uptake remains limited in some environments, as large companies favor speed over integration with humans, especially since lightweight robots are not optimal for certain tasks. A balance among safety, speed, and versatility would encourage investment in lightweight robots.

- While autonomous guided vehicles (AGVs) are perceived by some to be beneficial for logistics applications, their integration within a factory can be hampered by an unclear value proposition. The introduction of more robust and more reliable sensing systems, as well as the integration of IoT and cloud computing, can help companies expand the infrastructure of AGVs to introduce smart fleet management and enhance production flow.

- Finally, better data infrastructures could help companies make "smart data from big data," as a large multinational put it. As it stands, companies are resistant to investing in these infrastructures, as a clear benefit does not currently exist.

The Path Ahead: Research Directions, Solutions, and Recommendations

Based on our study of how these companies have experimented with and integrated these technologies, we can recommend improvements in the following eight domains:

1. Perception: These technologies pose a key limitation, both in the robustness of existing systems and in their use in downstream subsystems (such as grasping). We believe that researchers should focus their efforts on improving the robustness of perception capabilities in factory environments, particularly in migrating recent advances (such as in methods involving deep learning) to be more effective on the factory floor. Such migrations require methods to scale appropriately, as vast amounts of data are unlikely to be available in such domains, and to ensure robustness to environmental variations (such as changes in lighting). Regarding digital twins, improvements in perception could refine large-scale representations of digital environments, allowing for more accurate emulation of factory workcells, and highlighting anomalous or suboptimal operations.

2. Intelligent gripping: Pick and place is an essential robotics task. However, maneuvering objects in less constrained factory environments or allowing variations in the size and pose of a part, require a high degree of robotic intelligence. Fully automated generalized bin-picking systems are an immediate area of focus for many companies and a partially solved problem. For the

system to work efficiently, robot vision and sensory perception need to be advanced enough for robots to process objects from a pile of randomly distributed or scattered objects and pick them up. Research into dexterous in-hand manipulation, and improving technologies for tactile sensing and bin picking, including gripper design and grasp planning, in the context of a factory environment is an important research direction, as these technologies are critical to more flexible operations. Along with perception challenges, gripping remains one of the most limiting factors of automation in factories today.

3. Safe, collaborative robots: There are several areas of improvement here, including integration of human behavior prediction into robot path planning, for better safety and collaboration; improved tracking in dynamic workspaces; as well as demonstrating, through viable working models, the advantages of collaborative workcells and robot assistance to human-led operations. Again, making sure that the entire robotic system, including the tasks that the human performs, is safe to work with should be a priority.

4. Autonomous guided vehicles: An AGV can use a navigation technique called SLAM, simultaneous localization and mapping, in lieu of traditional navigation techniques to localize itself within a space. However, at the moment, the application of the technology in industry is still emerging. While SLAM provides robust or versatile data association, which is the act of associating detected features or landmarks (like a wall or other obstacles) with previous measurement, it is still hard to quantify how SLAM can improve logistical operation. Standards for fleet management are still emerging and are necessary in order to fully realize the benefits of AGVs for logistics. In addition, current SLAM capabilities need to be enhanced for the technology to be sufficient for mobile manipulation (i.e., if a robot is mounted on the vehicle).

5. Interfaces and programming: Programming robots is a difficult and expensive task, requiring time investment and special expertise. Research into human-robot interaction and methods to simplify the teaching or programming of robots, such as programming by demonstration and other methods not conditional on previous or significant programming expertise, are extremely valuable, especially those that allow the robot to generalize its behavior. These can ease skill requirements and, in turn, lower integration costs, resulting in wider use and application of robotics. A viable research direction worth considering is one that enables users to use semantic descriptions of work processes, workpieces, and workcells along with a graphical programming interface to program the robot.

6. Simulation: More work needs to be done to enhance digital simulation techniques, such as digital twins, to include, for instance, more detailed and fine-grained simulations of workcells or manufacturing lines. While VR and AR systems are promising avenues of research, factories could more immediately benefit from more high-fidelity models that typically yield better prototypes, which will be particularly useful as companies implement systems in the real world

based on these simulations and without requiring operational robots to be programmed ahead of implementation.

7. Worker-centered design: To back up anecdotal and experiential evidence, more research is needed into how design and integration processes are affected by contributions of workers, and how this affects performance and overall production cycles. In the long run, this can create a working framework for governing and evaluating human-machine interactions in industrial settings.

8. Cloud systems: Cloud systems promise to connect and control operations on the factory floor through the use of sensor data. However, so far, this vision has not been realized. Wide-scale sensor integration incurs heavy costs and a possible overhaul of company infrastructure. At this point, many companies say that it is difficult to make sense of the data that they collect from factory operations, and that they do not know how to extract and extrapolate useful information from it. Work toward how to extract meaningful information from data is therefore a valuable next step.

Endnotes

1. Industrial robot https://www.sciencedaily.com/terms/industrial_robot.htm.

2. IFR. 2019. "World Robotics 2019." Tech. rep. International Federation of Robotics.

3. Lobova, S.V., N.V. Bykovskaya, I.M. Vlasova, and O.V. Sidorenko. 2019. "Successful experience of formation of Industry 4.0 in various countries." In: *Industry 4.0: Industrial Revolution of the 21st Century*. Springer. 121–129.

4. Lu, Y. 2017. "Industry 4.0: A survey on technologies, applications and open research issues." *Journal of Industrial Information Integration*. 6: 1–10.

5. Horst, J. and F. Santiago. "What can policymakers learn from Germany's Industrie 4.0 development strategy?" In: Inclusive and Sustainable Industrial Development Working Paper Series WP 22, United Nations Industrial Development Organization (2018) https://www.unido.org/api/opentext/documents/download/11712839/unido-file-11712839.

6. Rajkumar, R., I. Lee, L. Sha, and J. Stankovic. 2010. "Cyber-physical systems: The next computing revolution." In: Design Automation Conference. IEEE. 731–736.

7. Monostori, L., B. Kádár, T. Bauernhansl, S. Kondoh, S. Kumara, G. Reinhart, O. Sauer, G. Schuh, W. Sihn, and K. Ueda. 2016. "Cyber-physical systems in manufacturing." *CIRP Annals*. 65(2): 621–641.

8. Furlough, Caleb, Thomas Stokes, and Douglas J. Gillan. Attributing Blame to Robots: I. The Influence of Robot Autonomy. In: *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 2019; 001872081988064 DOI: 10.1177/0018720819880641.

9. Hoffman, Guy, and Cynthia Breazeal. "Effects of anticipatory action on human-robot teamwork efficiency, fluency, and perception of team." Proceedings of the ACM/IEEE International Conference on Human-Robot Interaction. 2007.

10. Nikolaidis, Stefanos et al. "Improved human–robot team performance through cross-training, an approach inspired by human team training practices." *The International Journal of Robotics Research* 34.14 (2015): 1711–1730.

11. Huang, Chien-Ming, Maya Cakmak, and Bilge Mutlu. "Adaptive Coordination Strategies for Human-Robot Handovers." *Robotics: Science and Systems*. Vol. 11. 2015.

12. Unhelkar, Vaibhav V. et al. "Human-aware robotic assistant for collaborative assembly: Integrating human motion prediction with planning in time." *IEEE Robotics and Automation Letters* 3.3 (2018): 2394–2401.

13. ISO. 2012. "ISO 8373: 2012 (en) Robots and robotic devices—Vocabulary." Tech. rep. International Organization for Standardization.

14. Yao, F. et al. "Optimizing the Scheduling of Autonomous Guided Vehicle in a Manufacturing Process." In: Conference: 2018 IEEE 16th International Conference on Industrial Informatics (INDIN) (2018) DOI: 10.1109/INDIN.2018.8471979.

15. Tao, F., F. Sui, A. Liu, Q. Qi, M. Zhang, B. Song, Z. Guo, S. C.-Y. Lu, and A.Y.C. Nee. 2019. "Digital twin-driven product design framework." *International Journal of Production Research.* *57*(12): 3935–3953.

16. Ong, S. K. and A. Y. C. Nee. 2013. *Virtual and Augmented Reality Applications in Manufacturing*. Springer Science & Business Media.

17. OECD. 1997. "Small Business, Job Creation and Growth: Facts, Obstacles and Best Practices." Tech. rep. Organisation for Economic Co-operation and Development.

References

Ajaykumar, G. and C.M. Huang. 2020. “User needs and design opportunities in end-user robot programming.” In: *Companion of the 2020 ACM/IEEE International Conference on Human-Robot Interaction*. 93–95.

Alvite, J. G. 1987. “Robotic skin.” US Patent 4,694,231.

Argall, B.D., S. Chernova, M. Veloso, and B. Browning. 2009. “A survey of robot learning from demonstration.” *Robotics and Autonomous Systems*. 57(5): 469–483.

Bangemann, T., S. Karnouskos, R. Camp, O. Carlsson, M. Riedl, S. McLeod,

R. Harrison, A.W. Colombo, and P. Stluka. 2014. “State of the Art in Industrial Automation.” In: *Industrial Cloud-Based Cyber-Physical systems*. Springer. 23–47.

Billard, A., S. Calinon, R. Dillmann, and S. Schaal. 2008. “Survey: Robot pro- gramming by demonstration.” *Handbook of Robotics*. 59(BOOK_CHAP).

Bousmalis, K., A. Irpan, P. Wohlhart, Y. Bai, M. Kelcey, M. Kalakrishnan,

L. Downs, J. Ibarz, P. Pastor, K. Konolige, S. Levine, and V. Vanhoucke. 2018. “Using Simulation and Domain Adaptation to Improve Efficiency of Deep Robotic Grasping.” In: 2018 IEEE International Conference on Robotics and Automation (ICRA). IEEE. 4243–4250.

Bowman, S.L., N. Atanasov, K. Daniilidis, and G.J. Pappas. 2017. “Probabilistic Data Association for Semantic SLAM.” In: 2017 IEEE International Conference on Robotics and Automation (ICRA). IEEE. 1722–1729.

Burghardt, A., D. Szybicki, P. Gierlak, K. Kurc, P. Pietruś, and R. Cygan. 2020. “Programming of Industrial Robots Using Virtual Reality and Digital Twins.” *Applied Sciences*. 10(2): 486.

Cakmak, M. and A.L. Thomaz. 2012. “Designing Robot Learners That Ask Good Questions.” In: 2012 7th ACM/IEEE International Conference on Human-Robot Interaction (HRI). IEEE. 17–24.

“CE Marking.” https://europa.eu/youreurope/business/product-requirements/ labels-markings/ce-marking/index_en.htm. Accessed: 2020-05-13.

Chen, Y. 2017. “Integrated and Intelligent Manufacturing: Perspectives and Enablers.” *Engineering*. 3(5): 588–595.

Cheng, B., J. Zhang, G.P. Hancke, S. Karnouskos, and A.W. Colombo. 2018. “Industrial cyberphysical systems: Realizing cloud-based big data infrastructures.” *IEEE Industrial Electronics Magazine*. 12(1): 25–35.

Colim, A., P. Carneiro, N. Costa, C. Faria, L. Rocha, N. Sousa, M. Silva, A.C. Braga, E. Bicho, and S. Monteiro et al. 2020. “Human-Centered Approach for the Design of a Collaborative Robotics Workstation.” In: *Occupational and Environmental Safety and Health II*. Springer. 379–387.

Correll, N., K.E. Bekris, D. Berenson, O. Brock, A. Causo, K. Hauser, K. Okada, A. Rodriguez, J.M. Romano, and P.R. Wurman. 2016. “Analysis and Observations from the First Amazon Picking Challenge.” *IEEE Transactions on Automation Science and Engineering*. 15(1): 172–188.

De Schutter, J. and H. Van Brussel. 1988. “Compliant robot motion I. A formalism for specifying compliant motion tasks.” *The International Journal of Robotics Research*. 7(4): 3–17.

Dissanayake, M.G., P. Newman, S. Clark, H.F. Durrant-Whyte, and M. Csorba. 2001. “A solution to the simultaneous localization and map building (SLAM) problem.” *IEEE Transactions on Robotics and Automation*. 17(3): 229–241.

Dizdarević, J., F. Carpio, A. Jukan, and X. Masip-Bruin. 2019. “A survey of communication protocols for Internet of Things and related challenges of fog and cloud computing integration.” *ACM Computing Surveys* (CSUR). 51(6): 1–29.

Dragan, A.D., K.C. Lee, and S.S. Srinivasa. 2013. “Legibility and predictability of robot motion.” In: 2013 8th ACM/IEEE International Conference on Human-Robot Interaction (HRI). IEEE. 301–308.

Drost, B., M. Ulrich, N. Navab, and S. Ilic. 2010. “Model globally, match locally: Efficient and robust 3D object recognition.” In: 2010 IEEE Computer Society Conference on Computer Vision and Pattern Recognition. IEEE. 998–1005.

Duchaine, V., N. Lauzier, M. Baril, M.-A. Lacasse, and C. Gosselin. 2009. “A flexible robot skin for safe physical human robot interaction.” In: 2009 IEEE International Conference on Robotics and Automation. IEEE. 3676–3681.

Eder, K., C. Harper, and U. Leonards. 2014. “Towards the safety of human-in-the-loop robotics: Challenges and opportunities for safety assurance of robotic co-workers.” In: The 23rd IEEE International Symposium on Robot and Human Interactive Communication. IEEE. 660–665.

Elprama, B., I. El Makrini, and A. Jacobs. 2016. “Acceptance of collaborative robots by factory workers: A pilot study on the importance of social cues of anthropomorphic robots.” In: International Symposium on Robot and Human Interactive Communication.

Elprama, S.A., C.I. Jewell, A. Jacobs, I. El Makrini, and B. Vanderborght. 2017. “Attitudes of factory workers towards industrial and collaborative robots.” In: Proceedings of the Companion of the 2017 ACM/IEEE International Conference on Human-Robot Interaction. 113–114.

Fourie, C.K. 2019. “Adaptive Planning with Evidence Based Prediction for Improved Fluency in Routine Human-Robot Collaborative Tasks.” In: Proceedings of the AAAI Conference on Artificial Intelligence. Vol. 33. 9880–9881.

"Franka Emika Panda Robot." https://www.franka.de/technology. Accessed: 2020-07-27.

Freedman, R.G. and S. Zilberstein. 2017. "Integration of Planning with Recognition for Responsive Interaction Using Classical Planners." In: AAAI. 4581–4588.

Fryman, J. and B. Matthias. 2012. "Safety of industrial robots: From conventional to collaborative applications." In: ROBOTIK 2012; 7th German Conference on Robotics. VDE. 1–5.

Fujita, M., Y. Domae, A. Noda, G.A. Garcia Ricardez, T. Nagatani, A. Zeng,

S. Song, A. Rodriguez, A. Causo, I.M. Chen, and T. Ogasawara. 2019. "What are the important technologies for bin picking? Technology analysis of robots in competitions based on a set of performance metrics." *Advanced Robotics*: 1–15.

Gadre, S.Y., E. Rosen, G. Chien, E. Phillips, S. Tellex, and G. Konidaris. 2019. "End-user robot programming using mixed reality." In: 2019 International Conference on Robotics and Automation (ICRA). IEEE. 2707–2713.

Gunning, D. and D.W. Aha. 2019. "DARPA's Explainable Artificial Intelligence Program." *AI Magazine*. 40(2): 44–58.

He, K., X. Zhang, S. Ren, and J. Sun. 2015. "Delving Deep into Rectifiers: Surpassing human-level performance on ImageNet classification." In: Proceedings of the IEEE International Conference on Computer Vision. 1026–1034.

Henning, K. 2013. "Recommendations for implementing the strategic initiative INDUSTRIE 4.0."

Hentout, A., M. Aouache, A. Maoudj, and A. Isma. 2018. "Key challenges and open issues of industrial collaborative robotics." In: 2018 The 27th IEEE International Symposium on Workshop on Human-Robot Interaction: From Service to Industry (HRI-SI2018) at Robot and Human Interactive Communication. Proceedings. IEEE.

Hentout, A., M. Aouache, A. Maoudj, and I. Akli. 2019. "Human–robot interaction in industrial collaborative robotics: A literature review of the decade 2008–2017." *Advanced Robotics*. 33(15-16): 764–799.

Hoffman, G. and C. Breazeal. 2007. "Effects of anticipatory action on human-robot teamwork efficiency, fluency, and perception of team." In: Proceedings of the ACM/IEEE international conference on Human-robot interaction. 1–8.

Huber, A. and A. Weiss. 2017. "Developing human-robot interaction for an Industry 4.0 robot: How industry workers helped to improve remote-HRI to physical-HRI." In: Proceedings of the Companion of the 2017 ACM/IEEE International Conference on Human-Robot Interaction. 137–138.

IFR, Feb. 7, 2018. "Robot density rises globally." https://ifr.org/ifr-press- releases/news/robot-density-rises-globally.

Iqbal, T., S. Li, C. Fourie, B. Hayes, and J.A. Shah. 2019. "Fast online segmentation of activities from partial trajectories." In: 2019 International Conference on Robotics and Automation (ICRA). IEEE. 5019–5025.

ISO. 2016. "ISO 15066: 2016 (en) Robots and robotic devices–Collaborative Robots." Tech. rep. International Organization for Standardization.

Kadir, B.A., O. Broberg, and C.S. da Conceição. 2019. "Current research and future perspectives on human factors and ergonomics in Industry 4.0." *Computers & Industrial Engineering*: 137, 106004.

Kaess, M., A. Ranganathan, and F. Dellaert. 2008. "iSAM: Incremental smoothing and mapping." *IEEE Transactions on Robotics*. 24(6): 1365–1378.

Kapinus, M., Z. Materna, D. Bambušek, and V. Beran. 2020. "End-User Robot Programming Case Study: Augmented Reality vs. Teach Pendant." In: Companion of the 2020 ACM/IEEE International Conference on Human-Robot Interaction. 281–283.

Krizhevsky, A., I. Sutskever, and G.E. Hinton. 2012. "ImageNet classification with deep convolutional neural networks." In: *Advances in neural information processing systems*. 1097–1105.

"KUKA iiwa Industrial Robot." https://www.kuka.com/en-us/products/robotics-systems/industrial-robots/lbr-iiwa. Accessed: 2020-07-27.

Lamon, E., M. Leonori, W. Kim, and A. Ajoudani. 2020. "Towards an Intelligent Collaborative Robotic System for Mixed Case Palletizing." In: 2020 IEEE International Conference on Robotics and Automation (ICRA).

Lasota, P.A., T. Fong, and J.A. Shah. 2017. "A survey of methods for safe human-robot interaction." *Foundations and Trends in Robotics*. 5(4): 261–349.

Lasota, P.A., G.F. Rossano, and J.A. Shah. 2014. "Toward safe close-proximity human-robot interaction with standard industrial robots." In: 2014 IEEE International Conference on Automation Science and Engineering (CASE). IEEE. 339–344.

LeCun, Y., and Y. Bengio et al. 1995. "Convolutional networks for images, speech, and time-series." *The Handbook of Brain Theory and Neural Networks*. 3361(10): 1995.

Lee, M.H. 2000. "Tactile sensing: New directions, new challenges." *The International Journal of Robotics Research*. 19(7): 636–643.

Levine, S., C. Finn, T. Darrell, and P. Abbeel. 2016. "End-to-end training of deep visuomotor policies." *The Journal of Machine Learning Research*. 17(1): 1334–1373.

Mahler, J., J. Liang, S. Niyaz, M. Laskey, R. Doan, X. Liu, J.A. Ojea, and

K. Goldberg. 2017. "Dex-Net 2.0: Deep learning to plan robust grasps with synthetic point clouds and analytic grasp metrics." arXiv preprint arXiv:1703.09312.

Mainprice, J. and D. Berenson. 2013. "Human-robot collaborative manipulation planning using early prediction of human motion." In: 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems. IEEE. 299–306.

Meneweger, T., D. Wurhofer, V. Fuchsberger, and M. Tscheligi. 2015. "Working together with industrial robots: Experiencing robots in a production environment." In: 2015 24th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN). IEEE. 833–838.

Michalos, G., S. Makris, P. Tsarouchi, T. Guasch, D. Kontovrakis, and G. Chryssolouris. 2015. "Design considerations for safe human-robot collaborative workplaces." *Procedia CIRP*. 37: 248–253.

Mobley, R.K. 2002. *An Introduction to Predictive Maintenance*. Elsevier.

Moniz, A.B. and B.-J. Krings. 2016. "Robots working with humans or humans working with robots? Searching for social dimensions in new human-robot interaction in industry." *Societies*. 6(3): 23.

Mourtzis, D. 2019. "Simulation in the design and operation of manufacturing systems: State of the art and new trends." *International Journal of Production Research*: 1–23.

Mourtzis, D., M. Doukas, and D. Bernidaki. 2014. "Simulation in manufacturing: Review and challenges." *Procedia CIRP*. 25: 213–229.

"OPC Unified Architecture." https://opcfoundation.org/about/opc-technologies/opc-ua/. Accessed: 2020-07-30.

Pacaux-Lemoine, M.-P., D. Trentesaux, G.Z. Rey, and P. Millot. 2017. "Designing intelligent manufacturing systems through Human-Machine Cooperation principles: A human-centered approach." *Computers & Industrial Engineering*. 111: 581–595.

Pan, S.J. and Q. Yang. 2009. "A survey on transfer learning." *IEEE Transactions on Knowledge and Data Engineering*. 22(10): 1345–1359.

Perzylo, A., N. Somani, S. Profanter, M. Rickert, and A. Knoll. 2015. "Toward efficient robot teach-in and semantic process descriptions for small lot sizes." In: Proceedings of the Workshop on Combining AI Reasoning and Cognitive Science with Robotics, Robotics: Science and Systems (RSS).

Peternel, L., N. Tsagarakis, D. Caldwell, and A. Ajoudani. 2018. "Robot adaptation to human physical fatigue in human–robot co-manipulation." *Autonomous Robots*. 42(5): 1011–1021.

Qi, C.R., H. Su, K. Mo, and L.J. Guibas. 2017. "PointNet: Deep learning on point sets for 3D classification and segmentation." In: Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition. 652–660.

Quillen, D., E. Jang, O. Nachum, C. Finn, J. Ibarz, and S. Levine. 2018. “Deep reinforcement learning for vision-based robotic grasping: A simulated comparative evaluation of off-policy methods.” In: 2018 IEEE International Conference on Robotics and Automation (ICRA). IEEE. 6284–6291.

Ramos, F., R.C. Possas, and D. Fox. 2019. “BayesSim: Adaptive domain randomization via probabilistic inference for robotics simulators.” arXiv preprint arXiv:1906.01728.

“Robot Operating System (ROS).” https://www.ros.org/about-ros/. Accessed: 2020-05-13.

Ross, A.S. and F. Doshi-Velez. 2018. “Improving the adversarial robustness and interpretability of deep neural networks by regularizing their input gradients.” In: Thirty-Second AAAI Conference on Artificial Intelligence.

Sauppé, A. and B. Mutlu. 2015. “The social impact of a robot co-worker in industrial settings.” In: Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems. 3613–3622.

Steinmetz, F., V. Nitsch, and F. Stulp. 2019. “Intuitive Task-Level Programming by Demonstration Through Semantic Skill Recognition.” *IEEE Robotics and Automation Letters*. 4(4): 3742–3749.

Sünderhauf, N. and P. Protzel. 2012. “Switchable constraints for robust pose graph SLAM.” In: 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems. IEEE. 1879–1884.

Tan, C., F. Sun, T. Kong, W. Zhang, C. Yang, and C. Liu. 2018. “A survey on deep transfer learning.” In: 27th International Conference on Artificial Neural Networks. Springer. 270–279.

Tian, S., F. Ebert, D. Jayaraman, M. Mudigonda, C. Finn, R. Calandra, and S. Levine. 2019. “Manipulation by feel: Touch-based control with deep predictive models.” In: 2019 International Conference on Robotics and Automation (ICRA). IEEE. 818–824.

Tremblay, J., T. To, B. Sundaralingam, Y. Xiang, D. Fox, and S. Birchfield. 2018. “Deep object pose estimation for semantic robotic grasping of household objects.” In: Conference on Robot Learning (CoRL) 2018. arXiv preprint arXiv:1809.10790.

Turner, D. 2020. “Quirkos 2.2.” Software Resource.

Ulmen, J. and M. Cutkosky. 2010. “A robust, low-cost and low-noise artificial skin for human-friendly robots.” In: 2010 IEEE International Conference on Robotics and Automation. IEEE. 4836–4841.

“Universal Robots UR10e.” https://www.universal-robots.com/products/ur10-robot/. Accessed: 2020-07-27.

Welfare, K.S., M.R. Hallowell, J.A. Shah, and L.D. Riek. 2019. “Consider the Human Work Experience When Integrating Robotics in the Workplace.” In: 2019 14th ACM/IEEE International Conference on Human-Robot Interaction (HRI). IEEE. 75–84.

Wurhofer, D., T. Meneweger, V. Fuchsberger, and M. Tscheligi. 2015. “Deploying robots in a production environment: A study on temporal transitions of workers’ experiences.” In: IFIP Conference on Human-Computer Interaction. Springer. 203–220.

Wurhofer, D., T. Meneweger, V. Fuchsberger, and M. Tscheligi. 2018. “Reflections on Operators’ and Maintenance Engineers’ Experiences of Smart Factories.” In: Proceedings of the 2018 ACM Conference on Supporting Groupwork. 284–296.

Yousef, H., M. Boukallel, and K. Althoefer. 2011. “Tactile sensing for dexterous in-hand manipulation in robotics—A review.” *Sensors and Actuators A: Physical*. 167(2): 171–187.

Zanchettin, A.M., P. Rocco, S. Chiappa, and R. Rossi. 2019. “Towards an optimal avoidance strategy for collaborative robots.” *Robotics and Computer-Integrated Manufacturing*. 59: 47–55.

Zeng, A., S. Song, K.-T. Yu, E. Donlon, F.R. Hogan, M. Bauza, D. Ma,

O. Taylor, M. Liu, and E. Romo et al. 2018. “Robotic pick-and-place of novel objects in clutter with multi-affordance grasping and cross-domain image matching.” In: 2018 IEEE International Conference on Robotics and Automation (ICRA). IEEE. 1–8.

Zhu, Z. and H. Hu. 2018. “Robot learning from demonstration in robotic assembly: A survey.” *Robotics*. 7(2): 17.