DISRUPTOR REPORT **2019**

Disruption in Human Robot Collaboration

PRESCOUTER

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Drivers of Robotics Adoption in Industry

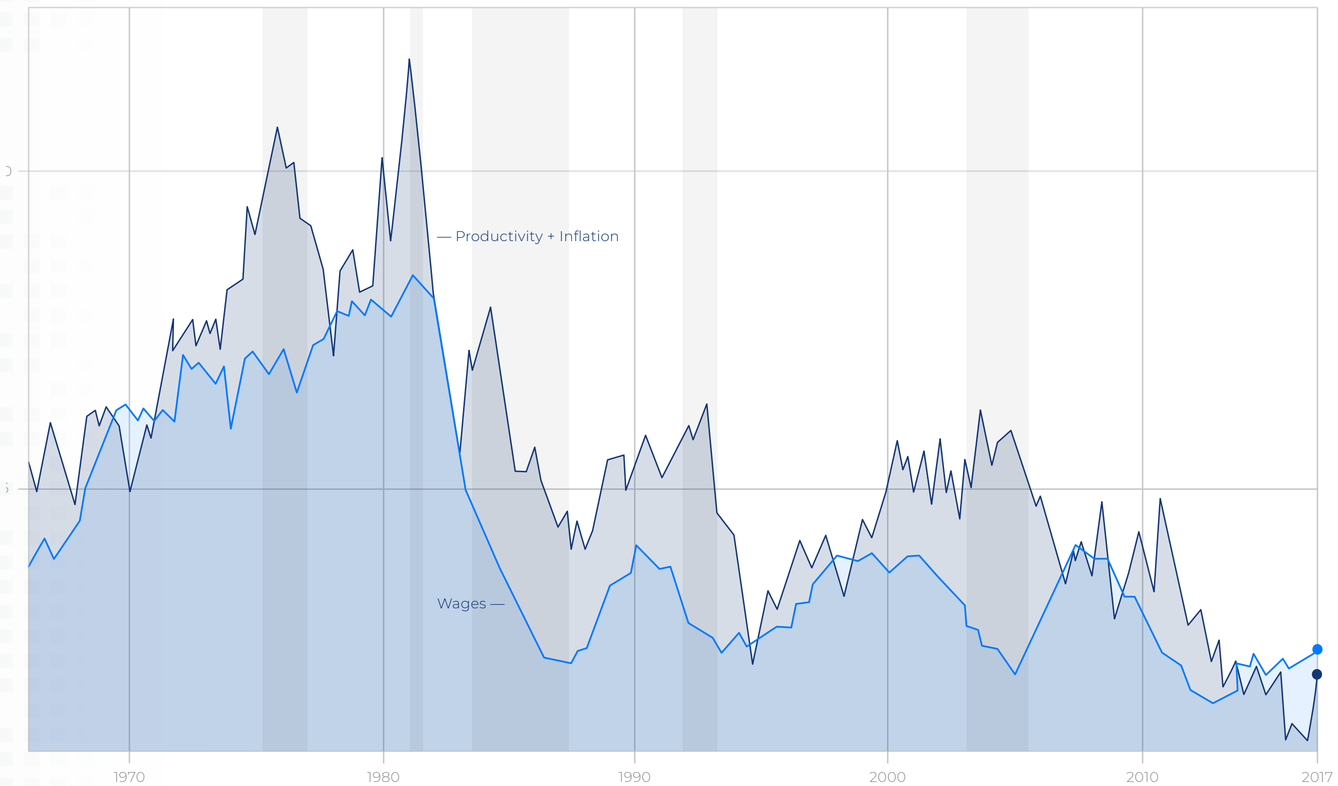
INTRODUCTION

The next great period of growth in manufacturing productivity will be driven, at least in part, by advances in machine sensing, engineering, and learning. These advances will provide robots with the capability to collaborate closely with workers and overcome variance. The original introduction of industrial machines and the production of goods in factories resulted in a dramatic increase in worker productivity over the course of the industrial revolution. In contrast, in the last 40 years, inflation-adjusted worker productivity in the United States has declined slightly (Fig. 1A).[1] Specifically, in the period after the Great Recession worker productivity in the manufacturing sector has shown, relatively, very little growth (Fig. 1B), though there has been substantial growth in robotics in the logistics and supply sector.[2] Interestingly, there has also been little growth in the rate of purchases of industrial robots in the United States in this same time frame, while there have been significant investments in robotics in the logistics and supply space as warehouses become increasingly automated (Fig. 1C).[3]

Industrial manufacturing robots primarily perform precise task sequences in sectors such as automotive and cell phone assembly; fields where variation is limited and the environment is tightly controlled. That the rate of growth in demand for manufacturing robots in the US has slowed may suggest it has hit a saturation point. This

FIG. 1A

ANNUAL RATE OVER PRECEDING TWO YEARS



Shaded areas indicate periods when productivity and inflation exceeded wage growth by more than two percentage points.
Wage growth is average hourly earnings for nonsupervisory workers; inflation measure is personal consumption expenditure price index.
Source: Bureau of Labor Statistics, Bureau of Economic Analysis

somewhat limited deployment may also be attributable to large industrial machines not necessarily aligning well with modern lean manufacturing principles, and suggests that there may be latent demand for new applications of robotics. In the logistics sector, there have been dramatic advances in the capability of robots to work collaboratively with humans using machine vision and dynamic obstacle avoidance. These advances, in broadening the scope of applications for these robots, may have contributed to increasing demand for logistics robots beyond the demand caused by the rising popularity of online shopping.

Lean manufacturing principles such as small batch size and fabrication-to-order have led to dramatic improvements in production and throughput by providing what customers need precisely when they need it.[4] An automated agile manufacturing facility should, in principle, be able to adjust to meet customer demand without the intervention of engineers who are not always on the floor. When there are only a few SKUs to consider, this is easy to manage; but in the face of SKU proliferation, there is demand for an enormous array of items, each of which may involve some tweak in the manufacturing, packing, or transportation process.[5] Current heavily automated factories that have been optimized to produce a particular product are very expensive to retool or reconfigure. As the capability of robots to both sense and adapt to their environment improves, they will be able to automate the production and transport of a broad array of goods while collaborating seamlessly with humans in the workplace. While this vision has been realized in some fields, such as logistics, further improvement of enabling technologies will allow robotics to assist with increasingly complex tasks. This will in turn make manufacturing more flexible, efficient, and adaptive to demand while opening up additional fields, such as healthcare and construction, to robotic labor.

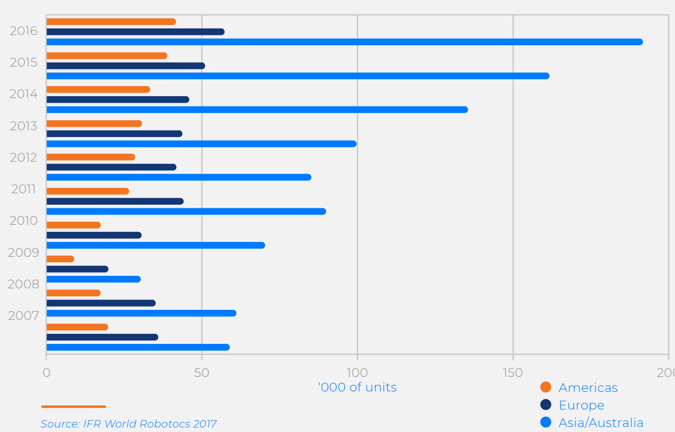
A coworker capable of lifting several tons who cannot hear, see, feel, or communicate with you would be difficult to work with and potentially hazardous. Many industrial robots must be kept separate from human workers on the floor, which is often done by encasing them in static protective cages. The next generation of robots must be capable of safely collaborating with humans and performing a broad array of tasks to meet the job at hand. Improved safety and adaptability would allow robots to work in environments with more variability such as construction sites, mines, and hospitals. Several firms have developed robots and automated guidance vehicles that use LiDAR-based obstacle detection systems to move through complex environments and dynamically avoid obstacles.[6] These are presently being used by companies such as Amazon to revolutionize warehouse logistics efficiency.[7] Improvements in obstacle detection systems and the modularity of robots are providing the foundation for an array of applications in fields such as enhanced manufacturing, urban infrastructure, medicine, and natural resource development.

AS THE CAPABILITY OF ROBOTS BOTH TO SENSE AND ADAPT TO THEIR ENVIRONMENT IMPROVES, THEY WILL BE ABLE TO AUTOMATE THE PRODUCTION AND TRANSPORT OF A BROAD ARRAY OF GOODS WHILE COLLABORATING SEAMLESSLY WITH HUMANS IN THE WORKPLACE.

Moving forward, making communication between non-technical personnel and robots more seamless may lead to explosive productivity growth by combining the domain knowledge of experts with the scalability of robotic action. This synthesis of human and robotic effort may dramatically impact productivity and forever change the way we work.

FIG. 1B

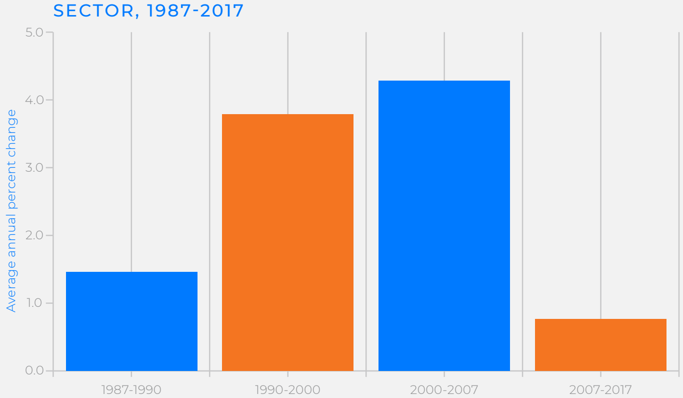
ESTIMATED WORLDWIDE ANNUAL SHIPMENTS OF INDUSTRIAL ROBOTS BY REGIONS



Source: IFR World Robotocs 2017

FIG. 1C

PRODUCTIVITY CHANGE IN THE MANUFACTURING SECTOR, 1987-2017



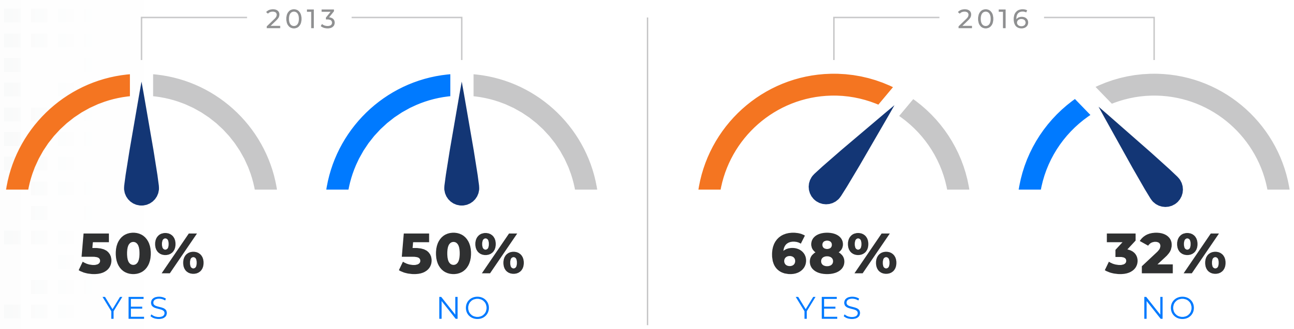
Source: U.S. Bureau of Labor Statistics

THE LOOMING SKILLS SHORTAGE

In 2017, a SHRM report found that fully half of HR professionals reported difficulty in recruiting for full-time regular positions, and by 2016 the number jumped to 68% (Fig. 2A).[8] About one-third of the HR professionals surveyed indicated that they were working without a training budget. This issue is further exacerbated by a lack of work experience (50% reported) and correct technical skills (38% reported), which makes it even harder to fill full-time positions (Fig. 2B).

FIG. 2A

MORE HR PROFESSIONALS REPORT DIFFICULTY RECRUITING FOR FULL-TIME REGULAR POSITIONS IN THE LAST 12 MONTHS

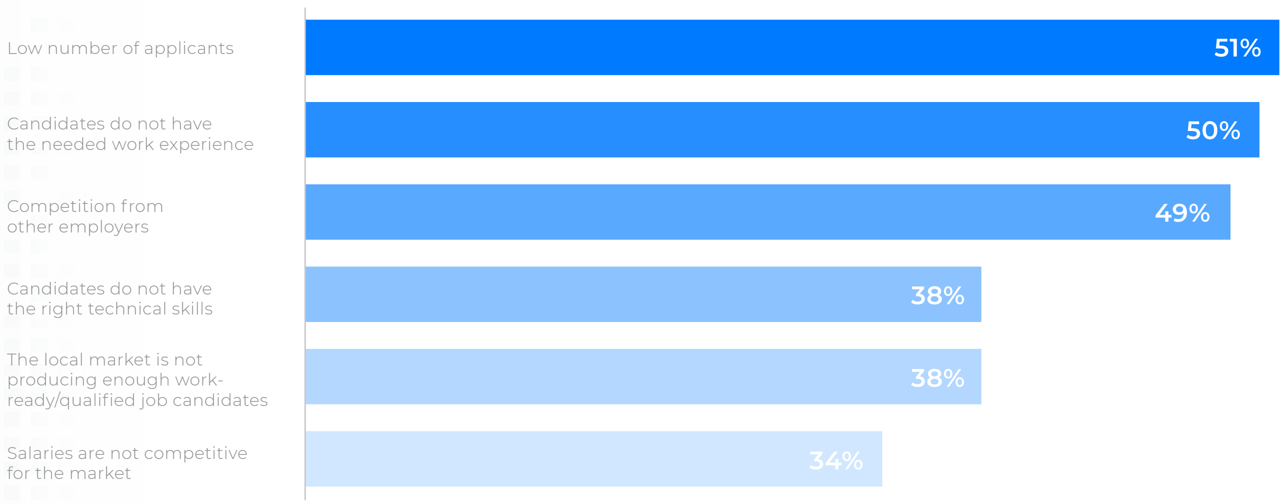


n=2,988 (2013); n=3,160 (2016). Respondents who answered "don't know" or "not applicable, have any full-time regular positions" were excluded from this analysis.
Source: The New Talent Landscape: Recruiting Difficulty and Skills Shortages (SHRM, 2016)

Importantly, this lack of technical skills is not only present in the classically high technology sectors that require advanced degrees such as computer programming or healthcare. HR professionals are also reporting that it is becoming increasingly difficult to hire in the construction and manufacturing sectors because of the skills deficit (Fig. 2C). The SHRM study reported that 2016 was the worst year for this phenomenon since 2010 (Fig. 2D). As has been described elsewhere in this report, the rate at which technology is changing is increasing. HR professionals across industries are finding that changing technology is the largest source of the skills gap that is making staffing increasingly difficult (Fig. 2E).

FIG. 2B

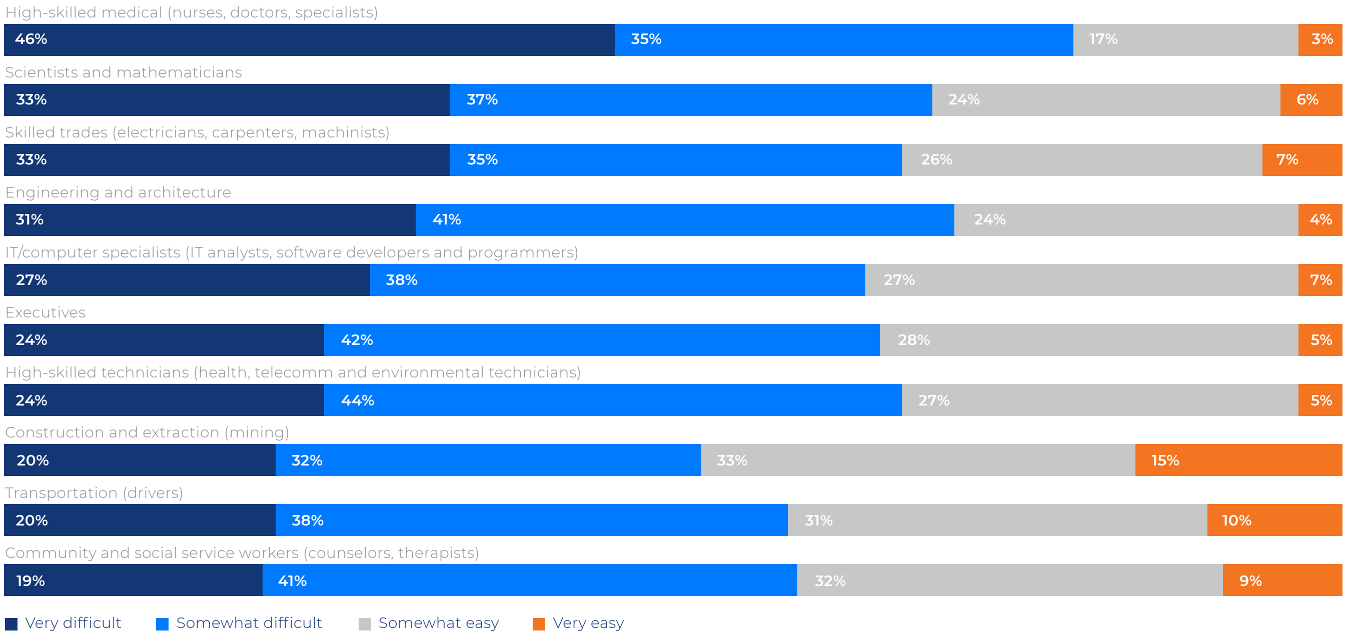
TOP REASONS ORGANIZATIONS EXPERIENCED HIRING DIFFICULTY FOR FULL-TIME REGULAR POSITIONS



n=2,114. Respondents who answered "don't know" were excluded from this analysis. Respondents could select multiple response options. Only respondents whose organizations were having difficulty hiring for full-time positions were asked this question.
Source: The New Talent Landscape: Recruiting Difficulty and Skills Shortages (SHRM, 2016)

FIG. 2C

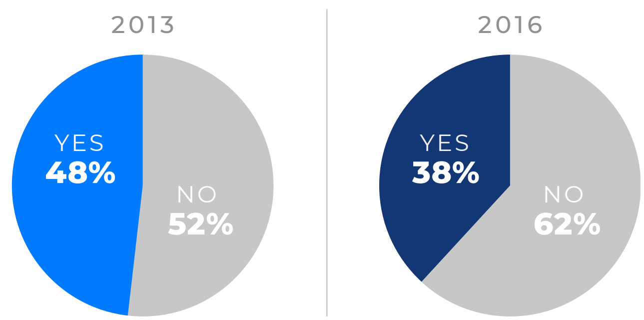
DIFFICULTY FILLING FULL-TIME REGULAR POSITIONS IN THE LAST 12 MONTHS, BY JOB CATEGORY



n=240–1,591. Respondents who answered "don't know" or "not applicable, did not hire this position" were excluded from this analysis.
Source: The New Talent Landscape: Recruiting Difficulty and Skills Shortages (SHRM, 2016)

FIG. 2D

ORGANIZATIONS REQUIRING NEW SKILLS FOR FULL-TIME REGULAR POSITIONS HIRED IN THE LAST 12 MONTHS

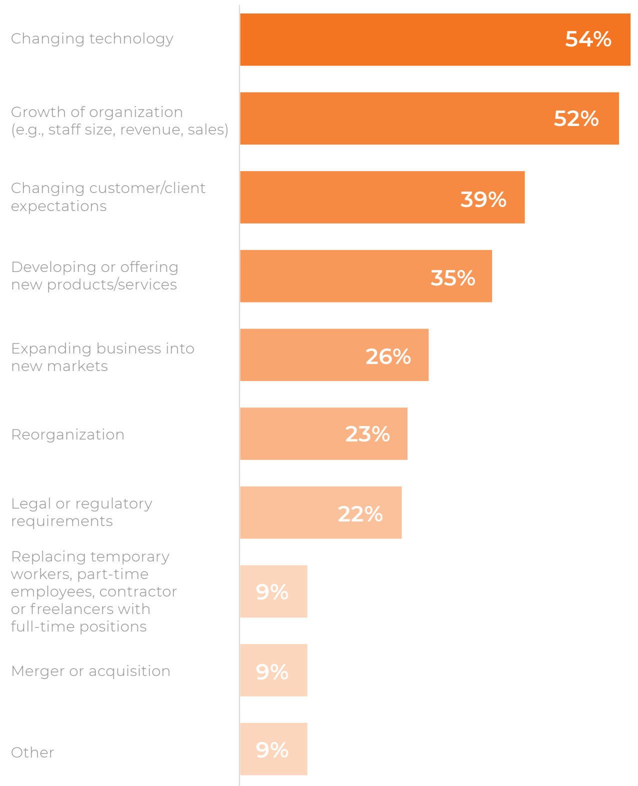


n= 2,641 (2013); n=2,734 (2016). Respondents who answered "don't know" were excluded from this analysis. Only respondents whose organizations were hiring full-time staff were asked this question.
Source: The New Talent Landscape: Recruiting Difficulty and Skills Shortages (SHRM, 2016)

AS HAS BEEN DESCRIBED ELSEWHERE IN THIS REPORT, THE RATE AT WHICH TECHNOLOGY IS CHANGING IS INCREASING. HR PROFESSIONALS ACROSS INDUSTRIES ARE FINDING THAT CHANGING TECHNOLOGY IS THE LARGEST SOURCE OF THE SKILLS GAP THAT IS MAKING STAFFING INCREASINGLY DIFFICULT.

FIG. 2E

REASONS THAT POSITIONS REQUIRE NEW SKILLS



n=999. Respondents who answered "don't know" were excluded from this analysis. Percentages do not equal 100% due to multiple response options. Only respondents whose organizations were hiring full-time positions that required new skills were asked this questions.
Source: The New Talent Landscape: Recruiting Difficulty and Skills Shortages (SHRM, 2016)

One of the simplest potential ways to address the skills shortage would be to make it as easy as possible for workers to adopt new technologies into their already existing practice; abrogating some of the need for expensive retraining. Current efforts in this vein have focused on developing new user interfaces (UI) and other ease of use systems. Disruptive advances in this space must instead facilitate the ability of personnel to rapidly incorporate new technology into their workflow without having to learn a new suite of skills (or a new UI) to perform a different class of task. Demonstration guided machine learning and/or direct interface between humans and machines, as opposed to direct programming of robotic actions, has been proposed as a way to increase the efficiency of human- robot collaboration. Invasive brain-machine interfaces that connect a chip that translates cortical signals into digital commands[9] have been proposed as one such alternative control method for robots. This technology has been instrumental in helping paralyzed patients, but it is expensive and extremely invasive, making it impractical for more broad use.

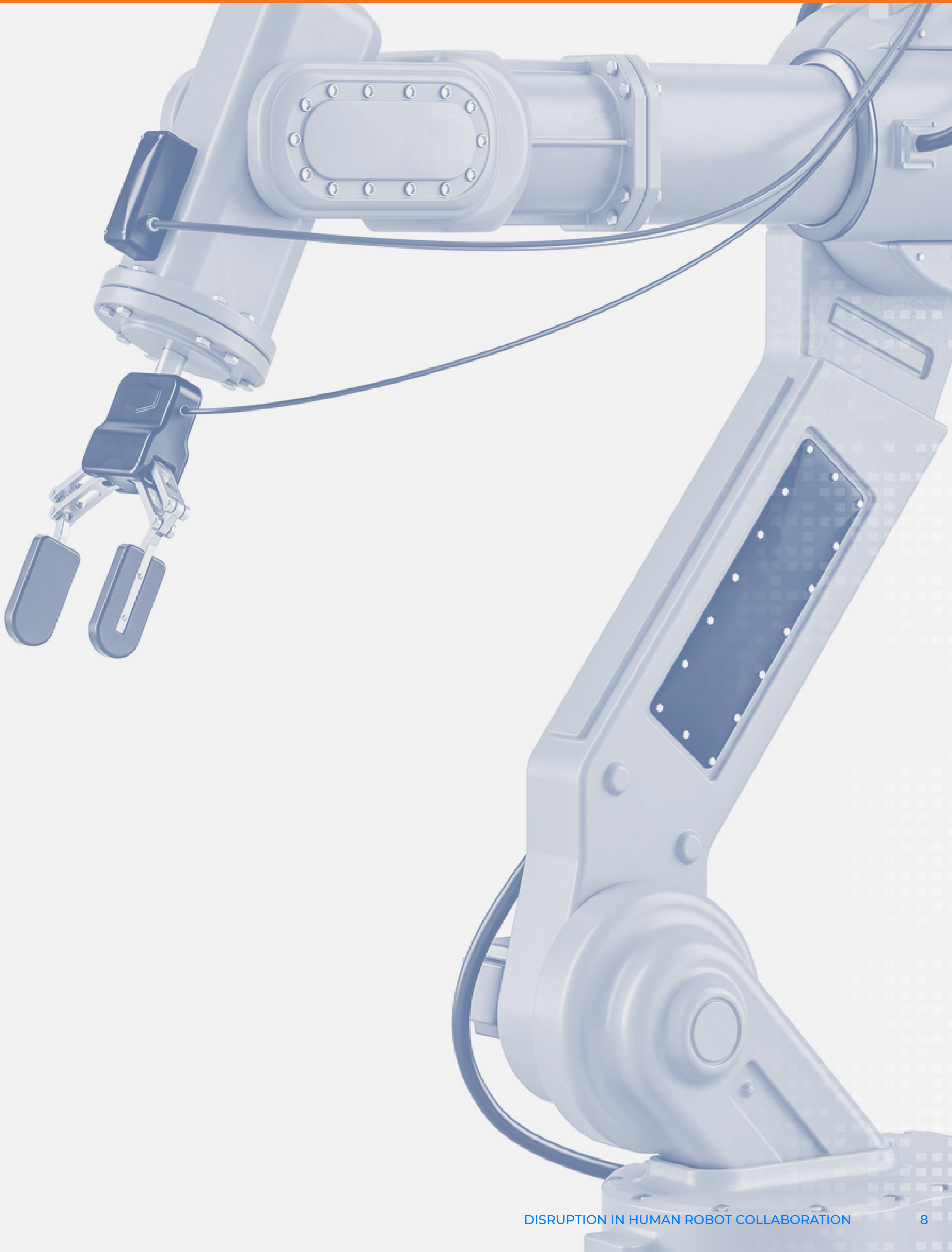
The next generation of robotic training and control will likely involve the combination of noninvasive inputs including,

1. ***Noninvasive electroencephalography-basedcomputer interfaces,***
2. ***Wearable motion or electronic activity sensors,***
3. ***Detection of eye movement,***
4. ***Decoding of motion capture, and***
5. ***Speech detection.***

Some combination of this suite of inputs, depending on the task, may permit a robot or even a robot swarm to rapidly interpret user behavior into complex commands in 3D space.

While this improved communication between robots and humans may facilitate more efficient collaboration, it would not eliminate the issue that direct-input controls tend to need to be calibrated, or trained, on a person-by-person basis. Overcoming this barrier will likely require the establishment of a feedback loop; the machine must learn how to be trained and then must communicate its needs to the user who can then improve how they are training the machine. This will involve the application of sophisticated machine learning programming on the back end and advances in UI/machine sensing on the front end to make the task of training robots as similar as possible to an artisan training an apprentice.

As the master trains the apprentice, their interaction with their pupil allows them to grow into a stronger mentor. The goal should be to replicate this dynamic between human directors and teams of robots to achieve the next generation of productivity growth. ◽



2 Bringing Robots to their Senses

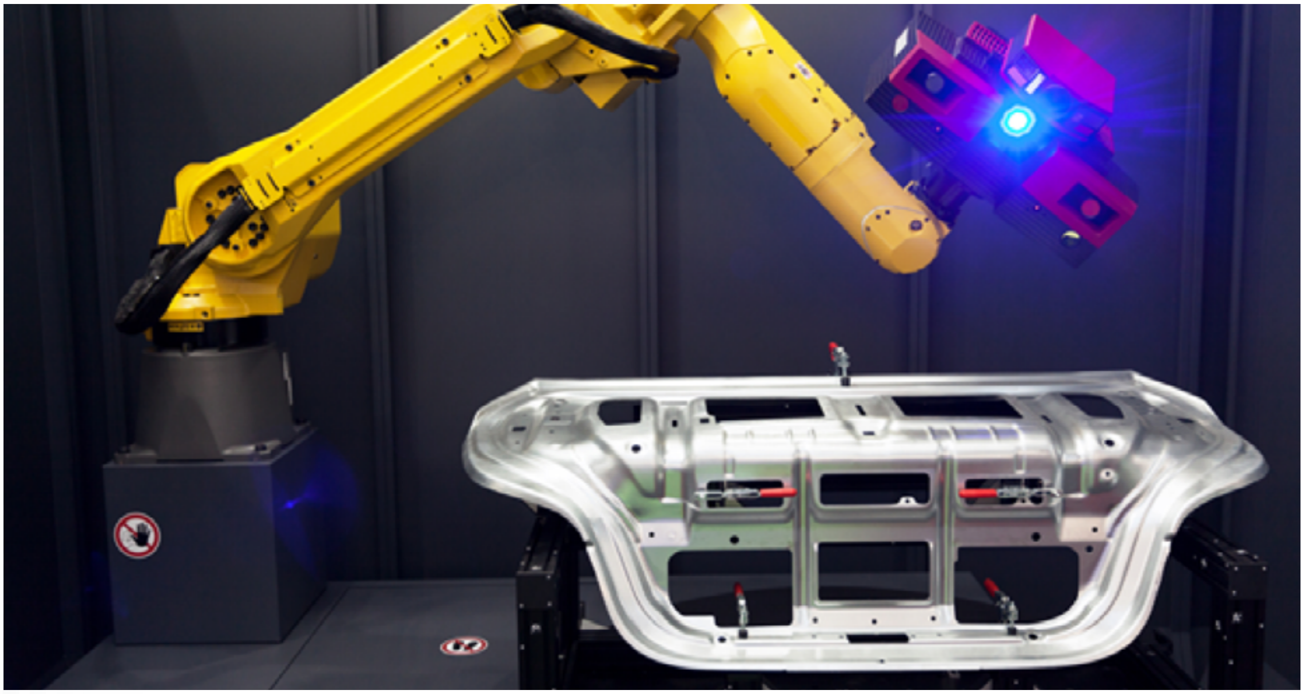
MACHINE VISION

Adapting to a changing environment, operating safely around people, and task-switching based on visual input is enormously helped by vision. Sensors that permit 3D machine vision are presently bulky and expensive. Small, inexpensive, and effective machine vision systems will permit the creation of robots that can work in much more dynamic environments while adapting their actions to fit the task at hand (Fig. 3).[10]

Machine vision is particularly important from a safety perspective; a robot that can move about a factory, construction site, or street must be able to avoid obstacles and people with high precision. Beyond obstacle avoidance, efficient 3D vision will permit machines to be trained using visual inputs from a human operator demonstrating tasks. Eventually, these robots will be trainable for an enormous range of actions by people who are domain experts themselves without the need for third-party engineer intervention.

INNOVATORS IN THE FIELD ARE WORKING TO MAKE LIDAR SMALLER, MORE ROBUST, AND CHEAPER. PROGRESS IN THIS TECHNOLOGY WILL EVENTUALLY PROVIDE MACHINE VISION APPLICATIONS FOR MOST ROBOTS, DRAMATICALLY INCREASING THEIR FLEXIBILITY, SITUATIONAL AWARENESS, AND ABILITY TO WORK IN CLOSE COLLABORATION WITH HUMANS.

FIG. 3



Source: https://www.visiononline.org/blog-article.cfm/Machine-Vision-Techniques-Practical-Ways-to-Improve-Efficiency-in-Machine-Vision-Inspection/79

LiDAR

Light detection and ranging (LiDAR) is very similar to sonar, but instead of sound it employs rapidly pulsed laser light, which permits a machine to "see" objects in 3D space. This capability can be used by machines to make robust 3D maps of their environment and identify objects in real time. While advances in this technology are some of the primary drivers in the autonomous car domain, current LiDAR systems are broadly considered to be bulky, sensitive to disruption, and expensive.[11]

For example, ***Leddar Tech*** is developing solid-state LiDAR that is resistant to mechanical disruption, which can cause significant errors in traditional LiDAR systems.[12] Importantly, their technology provides the same or better levels of sensitivity as other systems that use expensive lasers and mirrors for tasks such as accurate time-of-flight measurements and clear signal-to-noise ratios using inexpensive LEDs (Fig. 4A).[13] Their hardware and software algorithms permit a high sampling rate and may provide highly efficient machine vision for industrial robots that are subjected to difficult environments or occasional jostling. The cameras made by Leddar Tech are relatively small and are more sensitive relative to traditional LiDAR systems (Fig. 4B, 4C); however, Leddar's cameras currently have a narrow field of view. Depending on the application they would potentially require the use of multiple devices to achieve a sufficiently broad field, depending on the application. These cameras are currently being investigated for use in self-driving cars but could easily be adopted to a wide array of applications, particularly because of their small size, robustness, and relatively low price point.

FIG. 4A

FIG. 4C

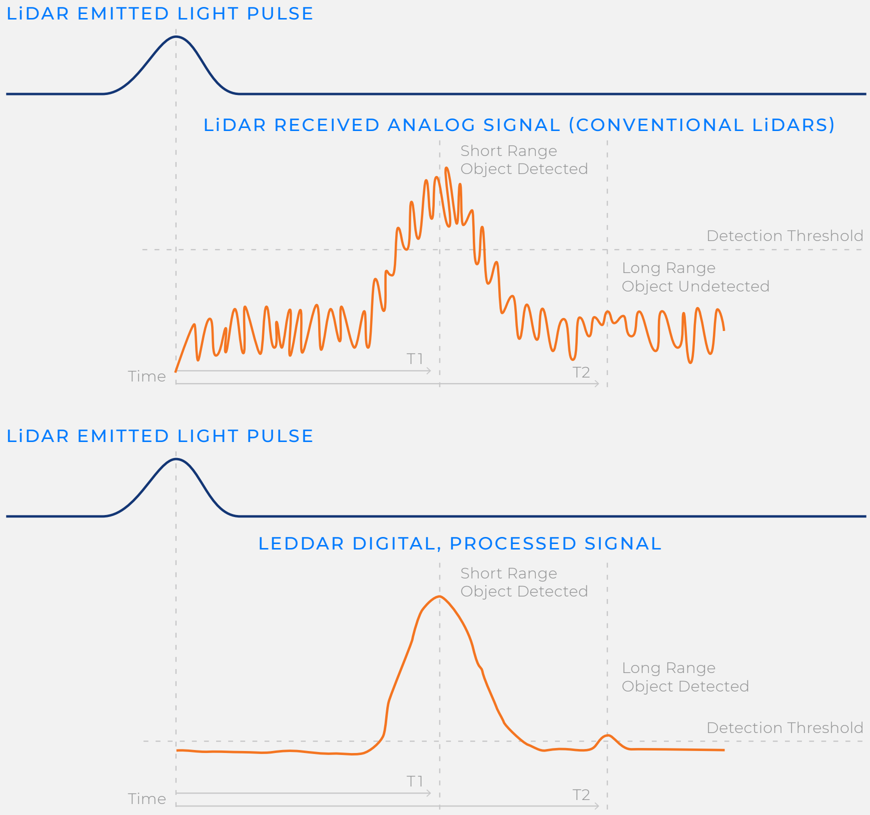
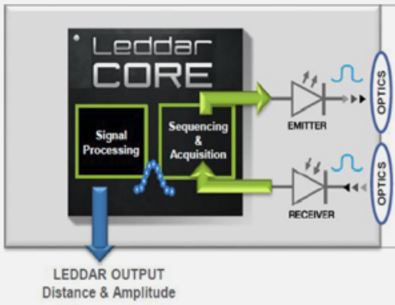


FIG. 4B



LEDDAR KEY DIFFERENTIATORS

- *Rather than working directly on the analog signal, Leddar samples the receive echo for the complete detection range of the sensor.*
- *Through patented methods, Leddar iteratively expands the sampling rate and resolution of this sampled signal.*
- *Utilizing sophisticated software-based algorithms, it analyzes the resulting discrete-time signal and recovers the distance for every object in its field of view.*

The Photonics Microsystems Group at MIT is working to dramatically miniaturize LiDAR systems by integrating them onto microchips (Fig. 5A, 5B). These chips can be produced in commercial CMOS foundries on standard 300-millimeter wafers, potentially making their unit production cost about $10. This chip has some limitations, since the current steering range of the beam is about 51 degrees, and it cannot create a 360-degree image by itself. Currently, their chips can only detect objects at 2 meters, but they are working on chips with a range of 100 meters.

Because of their small size and relatively inexpensive manufacturing costs, these chips have the potential to provide for the inclusion of multiple LiDAR sensors on a single device and expand machine vision applications to even basic consumer-facing robots. Inexpensive 360-degree vision achieved with arrays of these chips for robots would offer safe and effective collision avoidance, responsiveness to human gestures, and more adaptable designs.

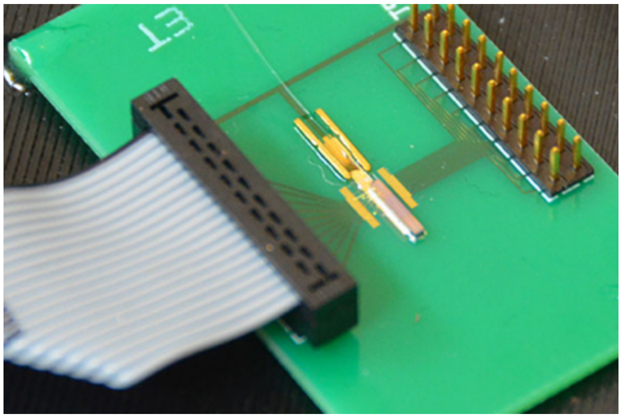
The Takashima Lab at the University of Arizona is another group working on miniaturization of LiDAR systems. Laser beam steering is a critical component of LiDAR image reconstruction and analysis, which normally contributes significantly to the bulk, expense, and fragility of LiDAR devices. At the SPIE Opto 2018 meeting, J. Rodriguez et al. demonstrated a small and inexpensive 3D-printed LiDAR detection system on a chip.[14]

While some groups are exploring micro-electromechanical systems for LiDAR beam steering, this group has developed a digital microirror device that is relatively small and provides an improved field of view relative to current LiDAR systems (48 degrees instead of 36 degrees) and a large beam size that is on par with existing LiDAR systems. While the present limitation of this approach is a reduced number of scanning points, the Takashima Lab and others are developing a multi-laser diode detector which may overcome this issue (Fig. 6A, 6B).Overall, this strategy shows some promise, with a number of devices showing moderate range despite the low cost and the ease of manufacture.

FIG. 5A

FIG. 5B

PROTOTYPE LIDAR CHIP AT DARPAS PENTAGON DEMO DAY MAY 2016

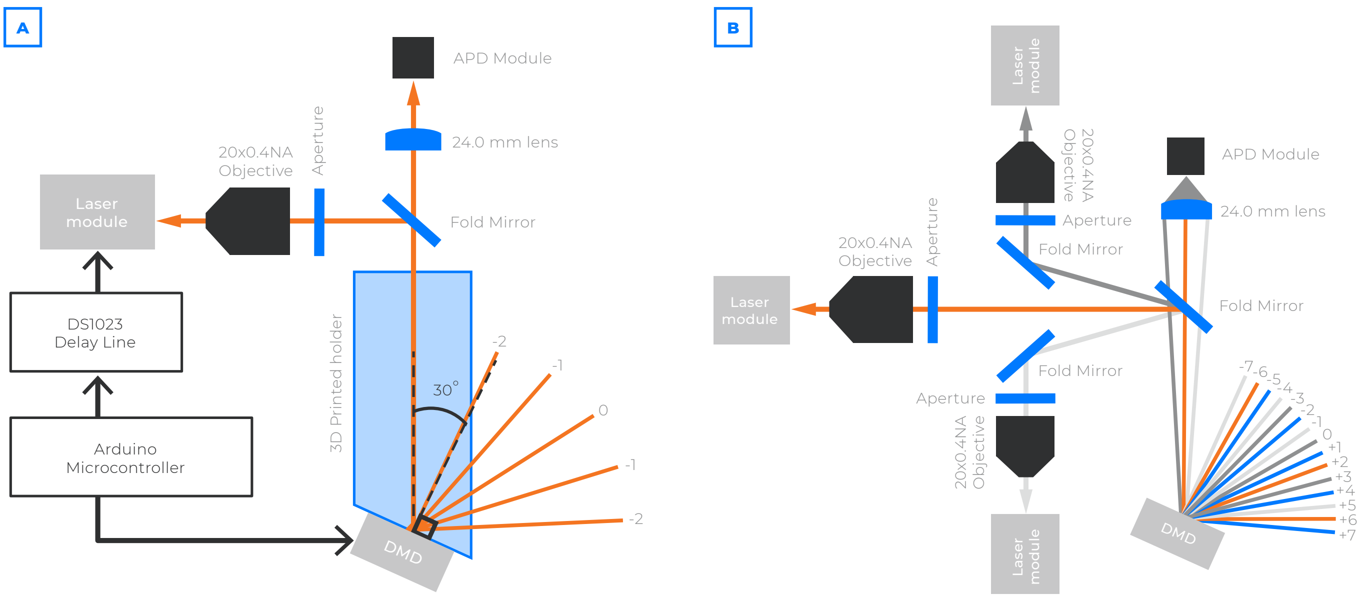


INEXPENSIVE 360-DEGREE VISION ACHIEVED WITH ARRAYS OF THESE CHIPS FOR ROBOTS WOULD OFFER SAFE AND EFFECTIVE COLLISION AVOIDANCE, RESPONSIVENESS TO HUMAN GESTURES, AND MORE ADAPTABLE DESIGNS.

Once developed and available, these chip-based LiDAR systems may be ideal for a suite of short-distance applications such as the detection of nearby obstacles and visually identifying objects to grab or manipulate. For example, robots with these sensors could be used to assemble or disassemble complex machines and identify objects by sight in shipping fulfillment centers, or these chips could be used in miniaturized pipeline inspection robots.

FIG. 6A

SCHEMATIC OF SETUP UTILIZING (A) A SINGLE LASER DIODE AND (BE) 3 LASER DIODES



ONCE DEVELOPED AND AVAILABLE, THESE CHIP-BASED LIDAR SYSTEMS MAY BE IDEAL FOR A SUITE OF SHORT-DISTANCE APPLICATIONS SUCH AS THE DETECTION OF NEARBY OBSTACLES AND VISUALLY IDENTIFYING OBJECTS TO GRAB OR MANIPULATE.

FIG. 6B

PERFORMANCE SUMMARY FOR TWO DMD TYPES AND TWO WAVELENGTHS OF LIGHT

DMD Model	Wavelength (mm)	Range	N_{LD}	N_{Order}	Total Number of Sean Angles	FOV (°)	Resolution (°)	Seam Rate (Lines/s)
DLP3000	905	55	5	5	25	49	1.9	160
DLP3000	1550	55	8	3	24	50	2.1	167
DLP9500	905	175	11	7	77	48	0.62	299
DLP9500	1550	175	18	5	90	60	0.65	256

Liquid lens–based autofocusing of light could facilitate robust real-time control of the light used in LiDAR sensing. This topic has been explored by research groups such as the ***Gopinath Lab at the University of Colorado***, which has outlined the concept of using a weak electromagnetic current to manipulate the shape of a series of lenses (Fig. 7A).[15] This technology is currently commercially available for other applications and is being sold by companies such as ***Cognex***, which provides off-the-shelf tunable liquid lenses for directing and concentrating lasers (Fig. 7B).[16] These lens systems are mechanically robust as they do not require the movement of physical parts to direct the laser path. The system is also relatively inexpensive for new application development, as it is already in production. These factors will potentially make this technology ideal for LiDAR applications, particularly in cases where the robot must be able to rapidly change the focus of the objective.

LIQUID LENS–BASED AUTOFOCUSING OF LIGHT COULD FACILITATE ROBUST REAL-TIME CONTROL OF THE LIGHT USED IN LIDAR SENSING.

FIG. 7A

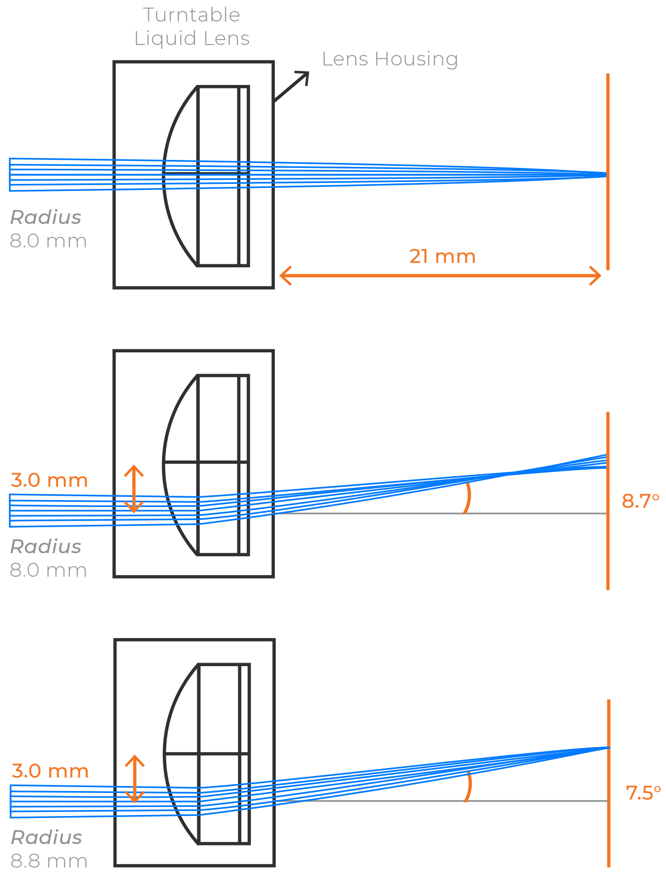
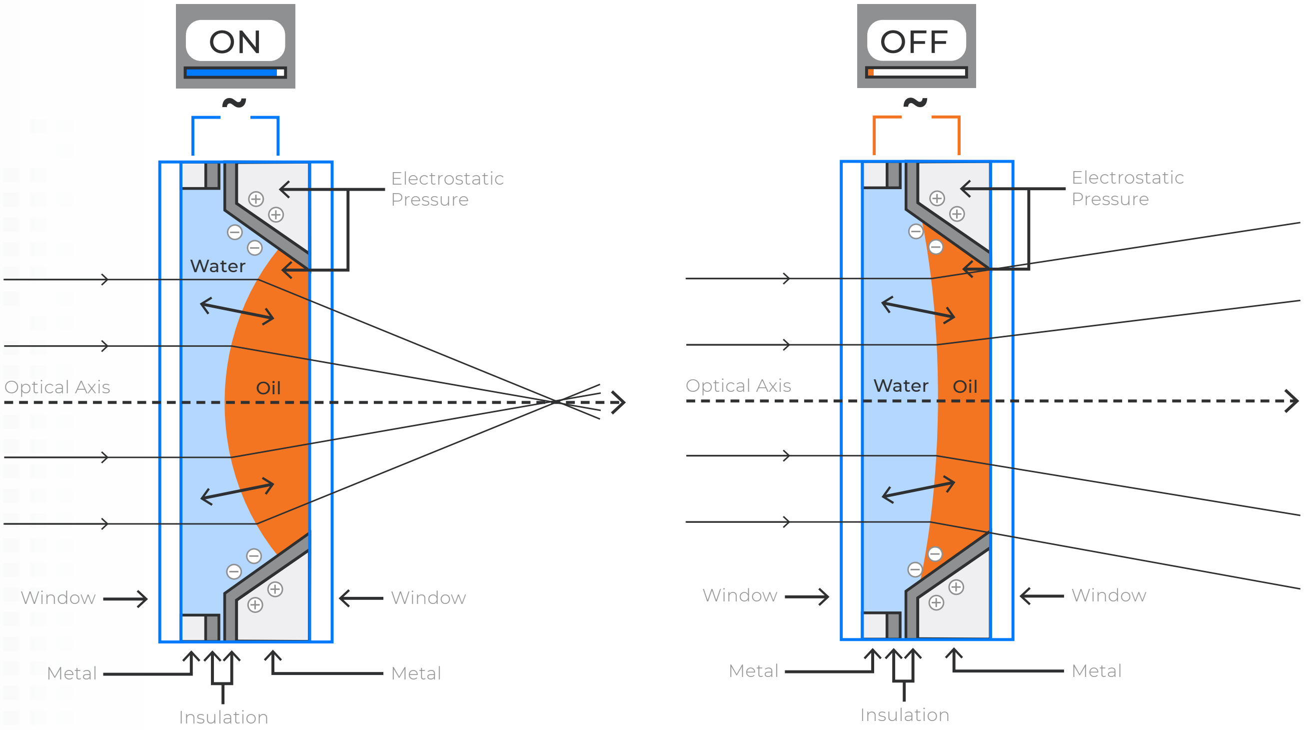


FIG. 7B

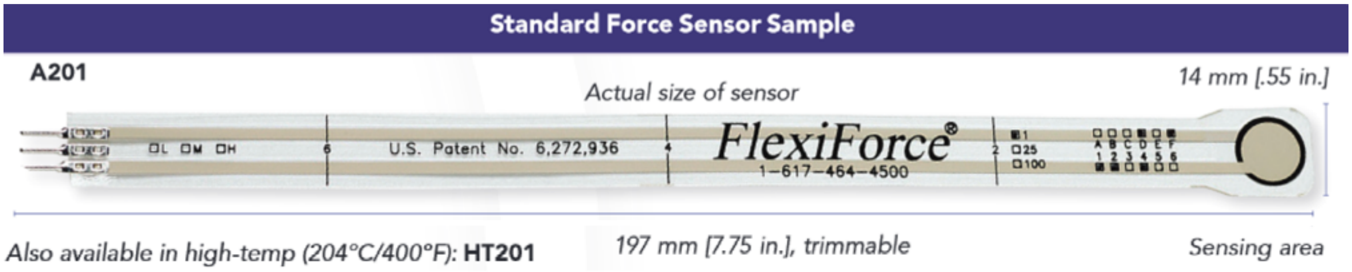


FORCE SENSING

Force-feedback sensing is critically important for work; it provides clues as to the strength and identity of an object and a mechanism to optimize the applied force. For example, it prevents us from smashing keyboards whenever we type and crushing fruit when we pick it. Machines capable of broad force sensing through a skin equivalent, as opposed to force sensing through a few joints, will make robots capable of handling a much broader array of tasks while adapting to the demands of an uncertain environment.

Past advancements in this field have been focused primarily on rotor sensors. Further improvement in dynamic force sensing on the surface of a robot, particularly its manipulators, will allow them to detect unexpected resistance. This could offer benefits in a huge number of fields. For instance, robots in industrial engineering could sense the material strength of objects and adjust accordingly to prevent stressing the material. In medicine, robots could sense skin resistance and apply gentle pressure when required in surgery or while helping patients move. In construction and inspection, robots could sense material weakness in structures and effect a local repair response as needed. In agriculture, robots could safely pick produce without destroying it. Developments in this space will likely center on the creation of broad, soft, skin-like force sensors that can provide context and location queues to robots.

FIG. 8A



Source: Tekscan.com

FIG.8B

FORCE SENSING USING INK TECHNOLOGIES

The company ***Tekscan*** is developing tactile pressure- and force- measurement sensors that are designed to be thin and durable. Further, these sensors are capable of registering their location in 3D space with high accuracy.[17] Tekscan's primary innovation is the creation of thin and durable force-sensitive ink. Because these sensors are so small (Fig. 8A), they can be custom designed to meet the requirements of objects of effectively any size or shape. The sensors are also relatively cheap to manufacture.

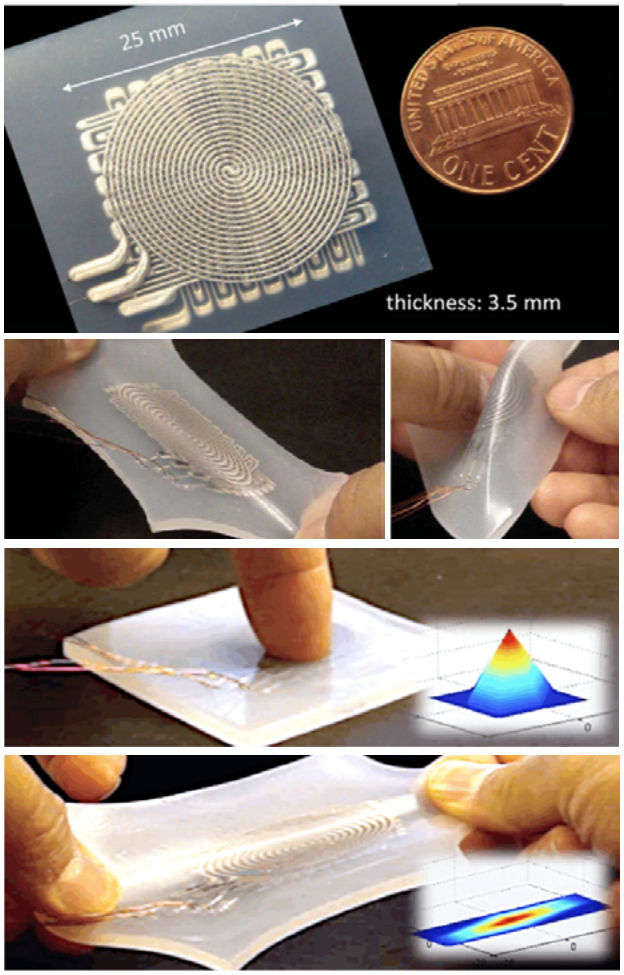
Peratech is another company working on force-sensing ink. They have developed a thin quantum tunneling composite material mixed with a polymer that is screen-printable (Fig. 8B). This composite changes its electrical resistance based on changes in applied force.[18] The resulting sensors are thin (200-um profile), can sense multiple touch points in parallel, and can detect 10g of force. Like the Tekscan force sensors, Peratech's quantum tunneling composite sensors are flexible, are capable of being printed on almost any surface, and can sense force through most standard materials.

SIMULATED SKIN FORCE SENSORS

Force-sensing systems that simulate skin should be soft, resistant, and capable of sensing pressure anywhere on their surface. This innovation, once commercialized, could make robots much more responsive to their surroundings and more capable of collaborating with humans. The designer would no longer need to anticipate sensor placement when designing a robot; instead, the entire working surface of the robot could act as a soft sensor. These sensors will be particularly valuable in fields demanding high precision, adaptability, or a soft touch, such as medicine, construction, and high-precision manufacturing.

There are a number of laboratories working on this technology, though no one is yet commercializing it. One group working on this is the ***Soft Robotics and Bionics Lab at Carnegie Mellon University***. They have recently developed an artificial skin system consisting of a highly stretchable silicone elastomer filled with conductive liquids capable of detecting multiple axes of strain and shear forces (Fig. 9).[19]

FIG. 9



CONCLUSIONS

Advancements in machine sensing have the potential to significantly increase the applications of machines by allowing them to work around people more safely and to adapt to changes in their environment or tasks without explicit input from a technician. By freeing humans from increasingly complex forms of labor while reducing the imposition of switching costs, companies following agile manufacturing practices may be able to use robots sporting a full suite of senses for an enormous array of tasks. As this field evolves, domain experts may even be able to train their robotic collaborators by example, allowing a firm to multiply the institutional expertise of their labor pool without resorting to motion capture in artificial conditions. This will in turn allow their coworker humans to focus on higher-productivity activities while acting as field commanders for robots.

This next generation of robotic sensing will permit robots to perform a significantly broader array of tasks. Many of these next-generation robots are already being developed in fields such as manufacturing, construction, infrastructure, and medicine. Further advances in robotics, such as those described in this report, will disrupt these industries by allowing for dramatically improved productivity in spaces that have traditionally been ill suited to automation.

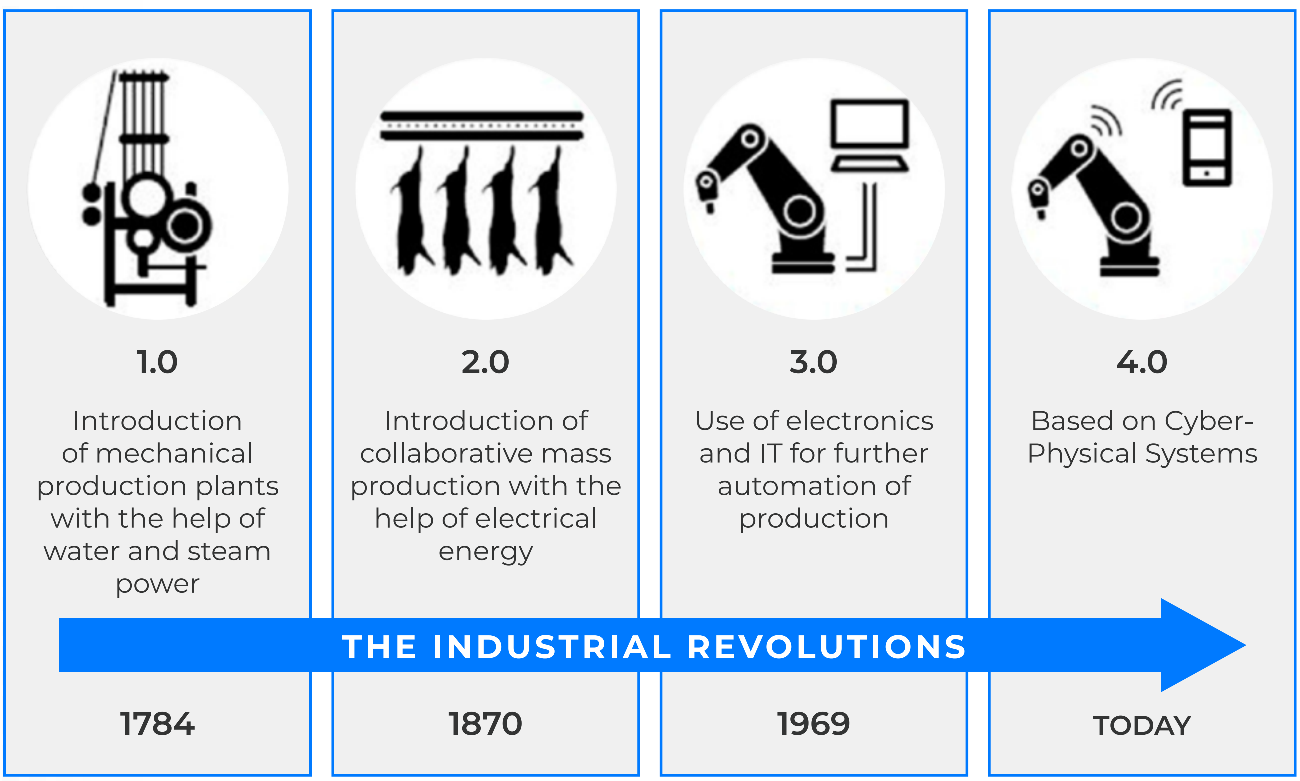
3 Emerging Applications of Sensing Robots

INTRODUCTION

As we develop the technologies that will allow robots to adapt to a dynamic environment in close proximity to humans, the number of tasks they will be capable of performing will increase by an order of magnitude. Robots capable of safely working in close collaboration with humans[20] and adapting to dynamic changes in the workplace will enable what has been termed "Industry 4.0" — paradigm whereby robots will ultimately work at a batch size of 1 and engage in preemptive error reporting and prevention.[21]

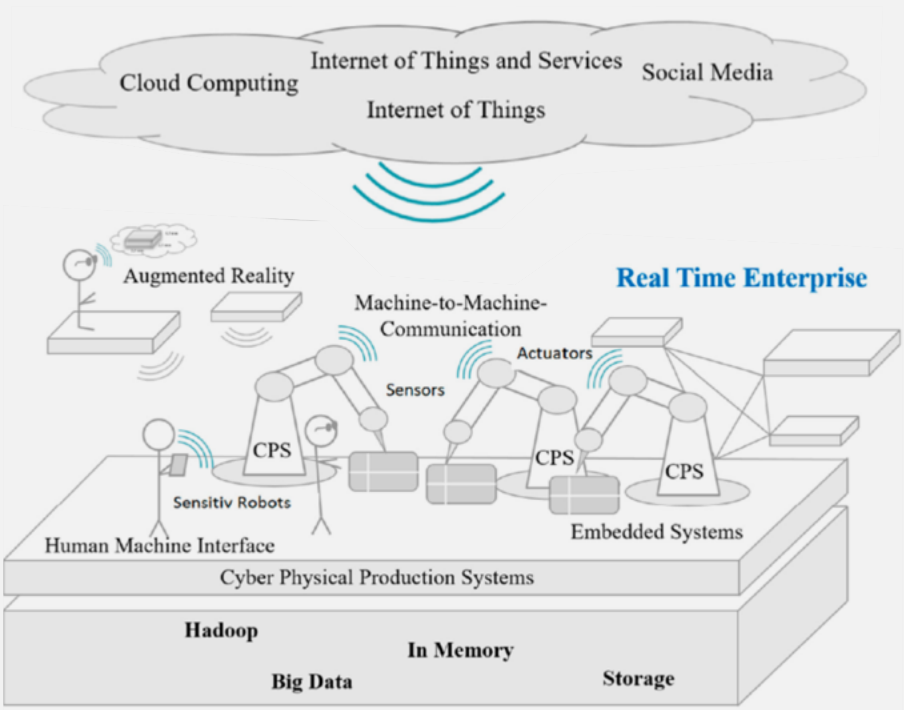
A substantial increase in productivity will result as industries transition to a system where robots can engage in skilled evaluation of the state of their work alongside human manufacturing employees who are following the principles outlined in The Toyota Way.[22] These advances will further make robots an integral component of smart-city technologies that clean, deliver, and repair. In the healthcare field, dynamic sensing robots will be a critical component of transporting, caring for, and perhaps even operating on patients. Similar capabilities will also permit autonomous probing for and harvesting of mineral deposits in hostile environments such as the sea floor without the need for direct or constant input from an operator. A number of robots have already been developed in these fields that are based on existing sensing systems and advances in machine learning. The next stage of development in this space will turn these innovations into the leading edge of a dramatically broadened field of applications for robots.

FIG. 10A



ROBOTS CAPABLE OF SAFELY WORK-ING IN CLOSE COLLABORATION WITH HUMANS AND ADAPTING TO DYNAMIC CHANGES IN THE WORK-PLACE WILL ENABLE WHAT HAS BEEN TERMED "INDUSTRY 4.0"—PARADIGM WHERE-BY ROBOTS WILL ULTI-MATELY WORK AT A BATCH SIZE OF 1 AND ENGAGE IN PRE-EMPTIVE ERROR REPORTING AND PREVENTION.

FIG. 10B



INDUSTRIAL ROBOTICS

For at least the next 5 years, industrial robotics is projected to see significant growth, approaching a CAGR of 12.5% between 2017 and 2023, for a total market size of $30.2 billion in 2023. Many countries, including the United States[23] and Germany,[24] are aiming to implement Industry 4.0 (a compilation of industrial practices that integrate robotics, AI, augmented reality, and the Internet of Things) to drive the next disruptive leap in worker productivity (Fig. 10A). Worldwide, the market for Industry 4.0 technologies is projected to grow from $76.64 billion in 2017 to $152.31 billion in 2022, with a CAGR of 14.72%.[25] Ideally, Industry 4.0 practices will allow humans to work with machines in smart factories. Within these factories, big data analysis, wireless cloud computing, edge sensor networks, and augmented reality will allow humans to interface with machines more effectively and produce products in smaller batch sizes more efficiently (Fig. 10B).[26] Presently, development of the Industry 4.0 paradigm is largely restricted to stationary robots wirelessly connected to a factory, with stationary sensors providing contextual input to the robots (Fig. 10C) with some logistics robots being used to automatically deliver parts from one part of the factory floor to another. As machine sensing technologies advance, become cheaper, and miniaturize, robots will be able to have these sensors integrated into their systems, thereby removing a major barrier to their capacity to move to where they are needed and perform the most critical tasks as part of a more dynamic factory floor. Current advances in industrial machine sensing and modularity are a sign of things to come and will be integral to the development of Industry 4.0.

FIG. 10C

For instance, the company ***Modbot*** has developed a modular industrial robot that sports a single arm and a series of adaptors that allow it to perform a huge array of tasks (Fig. 11A).[27] With this flexibility, the modbot maintains 6 degrees of freedom, a reach of 750 mm, and a lifting capacity of 7.5 kg (Fig. 11B). While this technology represents an example of modularity that still requires some user intervention, it is considerably less labor intensive than many current industrial robots.

If robots could adapt to a range of objects with variable dimensions and weight without needing to be refit for each application, they could dramatically improve the throughput and efficiency of the process they are involved in. The field of soft robotics may represent a means to this end through the development of biologically inspired grippers which can mimic hands or octopus tentacles that use force feedback and adaptable gripping surfaces to manipulate a wide range of objects.[28] ***Soft Robotics Inc.*** is a pioneer in the commercialization of this technology and has developed a range of soft robotic manipulators that can safely pick up an effectively limitless range of SKUs ranging from textiles to produce (Fig 11D).

FIG. 11A

6 DOF-C SPECIFICATIONS

The 6 DOF-C is a 6 degree of freedom collaborative robot configuration. It has a reach of 750 mm and a footprint of 1.5 x 1.5 meters with a payload of 7.5 kg.

- 6 *Servo*
- 0 *Bend (P-Type)*
- 2 *Straight*
- 1 *Brain*
- 1 *Electrical Breakout*
- 1 *Assembly Tool*
- 6 *Bend (L-Type)*
- 1 *Base*
- 1 *Power Suppy Unit (PSU)*
- 1 *Mechanical Breakout*
- 1 *I/O Module*

FIG. 11B

FIG. 11C

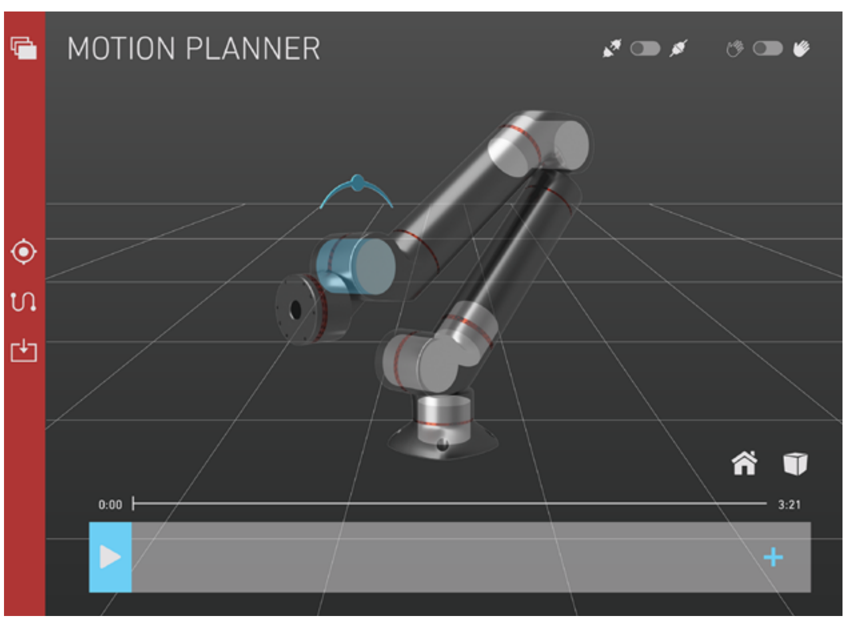
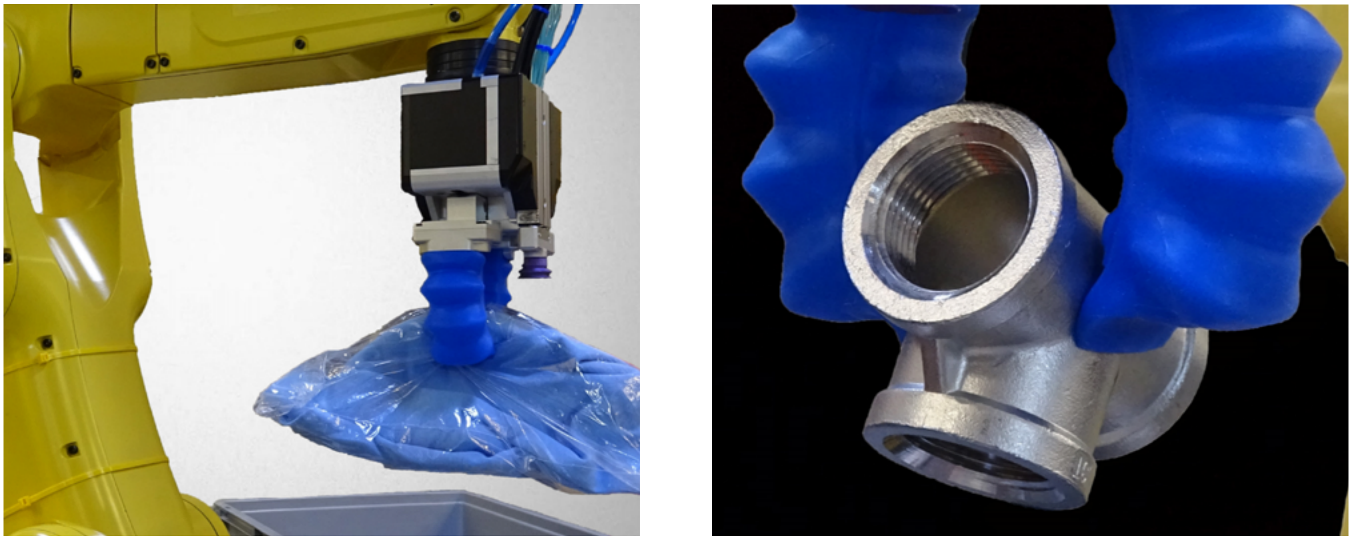


FIG. 11D



Another essential component enabling Industry 4.0 applications will be the ability of machines to sense and interpret a human's actions. This will be essential as human instructors try to teach the machine how to perform a task without having to program in the precise motions. The ***Mechanical Systems Control Lab at UC Berkeley*** has developed a number of tools that facilitate intuitive 2-way communication between robots and human operators.[29] In brief, these tools include stabilizers on the robot's structure that prevent vibration and allow for smooth mimicking of human actions (Fig. 12A). The robots in this laboratory use a combination of machine vision and force-sensing inputs to rapidly mimic the basic actions performed by the human robot trainer (Fig. 12B). This paradigm may eventually allow experts to train their robotic collaborators without the need for programming expertise.

SOFT ROBOTICS INC. IS A PIONEER IN THE COMMERCIALIZATION OF THIS TECHNOLOGY AND HAS DEVELOPED A RANGE OF SOFT ROBOTIC MANIPULATORS THAT CAN SAFELY PICK UP AN EFFECTIVELY LIMITLESS RANGE OF SKUS RANGING FROM TEXTILES TO PRODUCE.

FIG. 12A

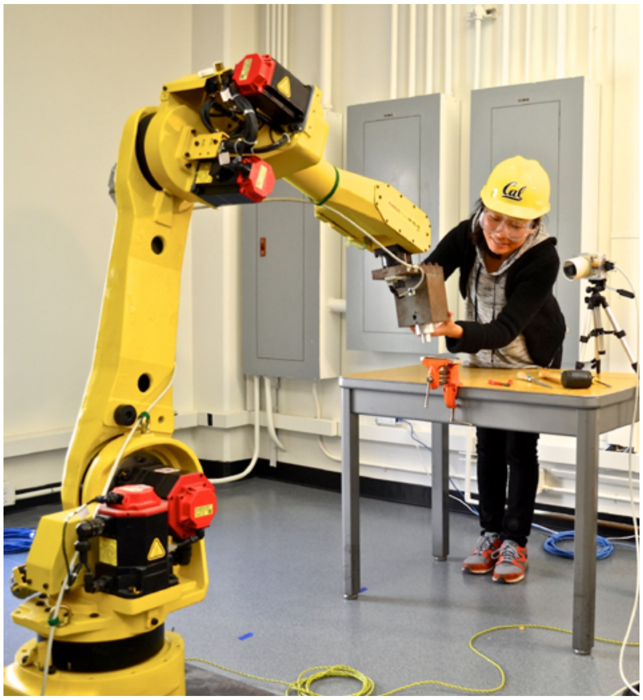
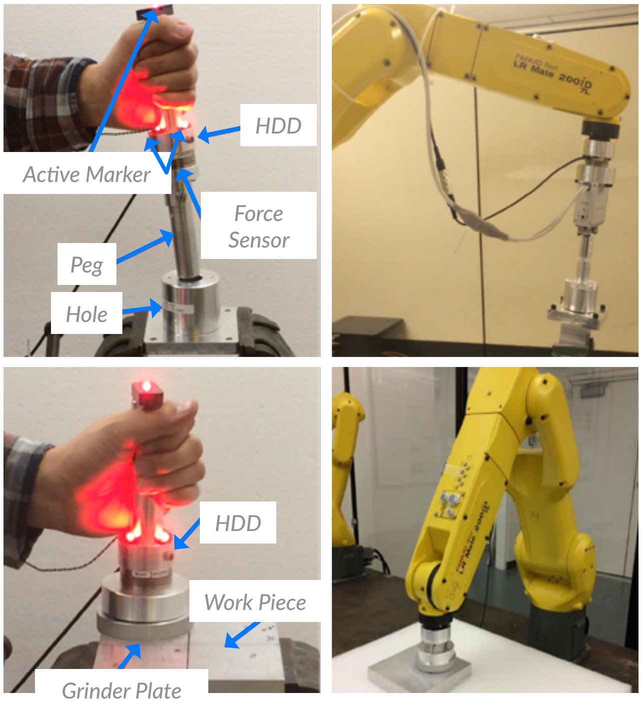


FIG. 12B



Today, many industrial robots are kept in cages to protect human workers and most industrial robots are used in fields requiring repetitive and precise motions in a near-sterile environment, such as car and phone manufacturing.

In the future, the advances described in this report will permit robots to move freely on the factory floor while applying learned behavior. This will in turn effectively allow skilled workers to become programmers capable of translating their deep domain knowledge into a smart robotics platform. This will have the follow-on benefit of keeping those who are most familiar with the industrial process in touch with the factory floor without the need for constant intervention by robotics experts.

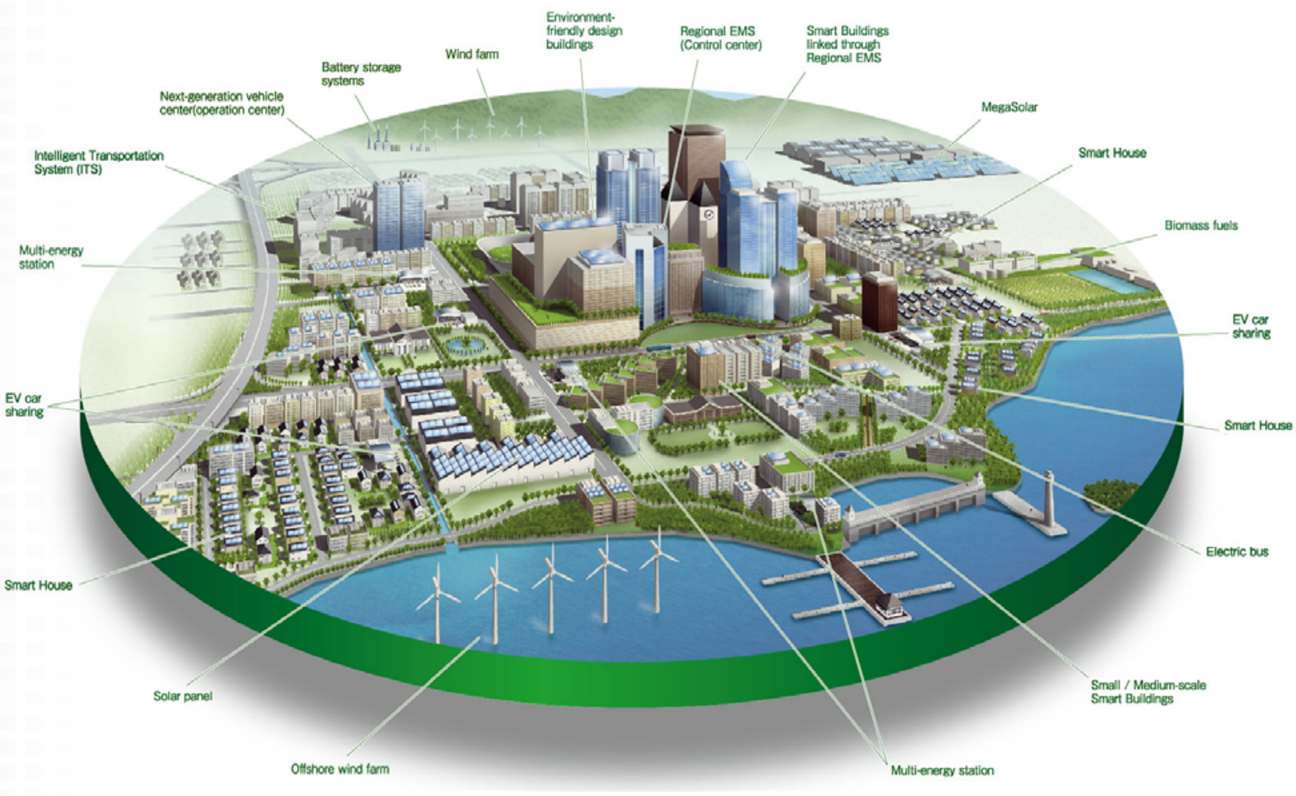
These same advances will allow robots to even leave the factory and begin working among people, making cities, farms, hospitals, and resource collection more efficient.

URBAN ROBOTICS

The concept of the smart city that can dynamically respond to the needs of its population captivates the imagination (Fig. 13). The overall investment in this space is estimated to be enormous and growing rapidly, with a worldwide market size of $424.68 billion in 2017 and expanding at a CAGR of 23.1% to an estimated $1.2 trillion in 2022.[30] As the United Nations has projected that the portion of the world's population living in urban areas will grow from the present 55% to 68% by 2050,[31] the demands on urban infrastructure will necessarily become more intense. Repair, maintenance, cleaning, and new construction will be critical needs that may be met with next-generation robots.

The Self Repairing Cities Project in the United Kingdom aims to tackle the challenge of zero disruption from street works in the country by 2050. This project is a collaboration between

FIG. 13



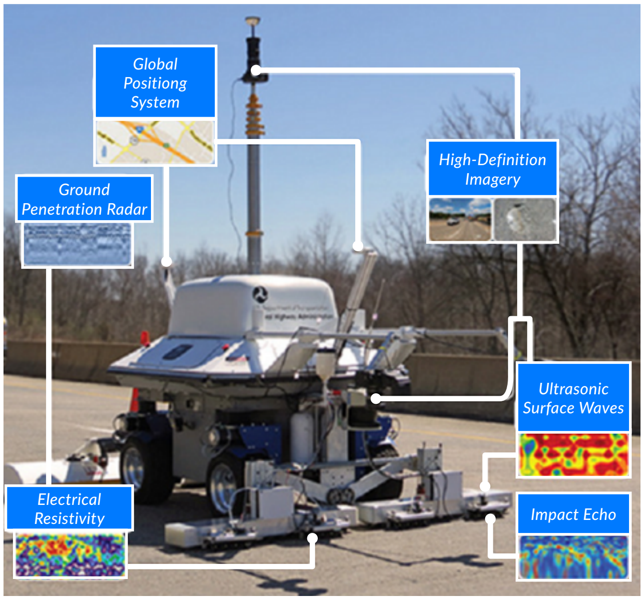
Source: https://medium.com/solar-microgrid/microgrid-technology-paving-the-way-towards-smart-cities-ed9cc55e57d

FIG. 14A

FIG. 14B

a number of academic groups in the United Kingdom such as the University of Leeds, the University of Birmingham, the University of Southampton, and University College London.[32] In brief, their research goal is to develop robots that can automatically identify, diagnose, and repair street works in a smart city. They are developing three classes of robots for this task. The first is a set of aerial drones capable of flying sections of road to the site of a pothole (Fig. 14A) or flying to a street lamp to repair it (Fig. 14B). The second class of robots encompasses ground vehicles that use machine vision to safely reach the work location, perceive holes in the road using a suite of onboard sensors, and fix them automatically while on site (Fig. 14C). Lastly, they are developing robots that travel along pipes looking for leaks or other damage that can then be corrected before the damage worsens (Fig. 14D). Each of these robot systems will greatly benefit from advances in sensing technology that make them safer, smaller, and more affordable for a city. Once implemented, they may become a valuable part of a smart city's infrastructure.

FIG. 14C



EACH OF THESE ROBOT SYSTEMS WILL GREATLY BENEFIT FROM ADVANCES IN SENSING TECHNOLOGY THAT MAKE THEM SAFER, SMALLER, AND MORE AFFORD-ABLE FOR A CITY. ONCE IMPLE-MENTED, THEY MAY BECOME A VALUABLE PART OF A SMART CITY'S INFRASTRUCTURE.

FIG. 14D

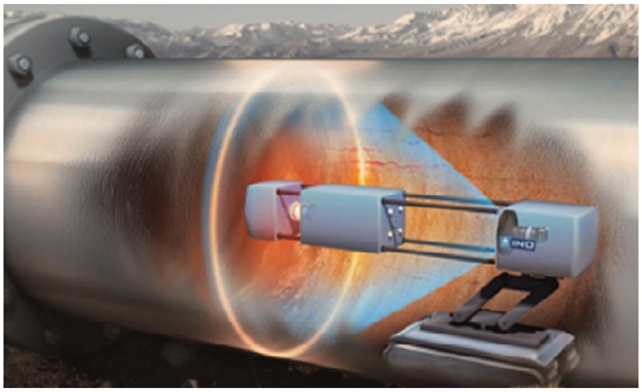


FIG. 15A

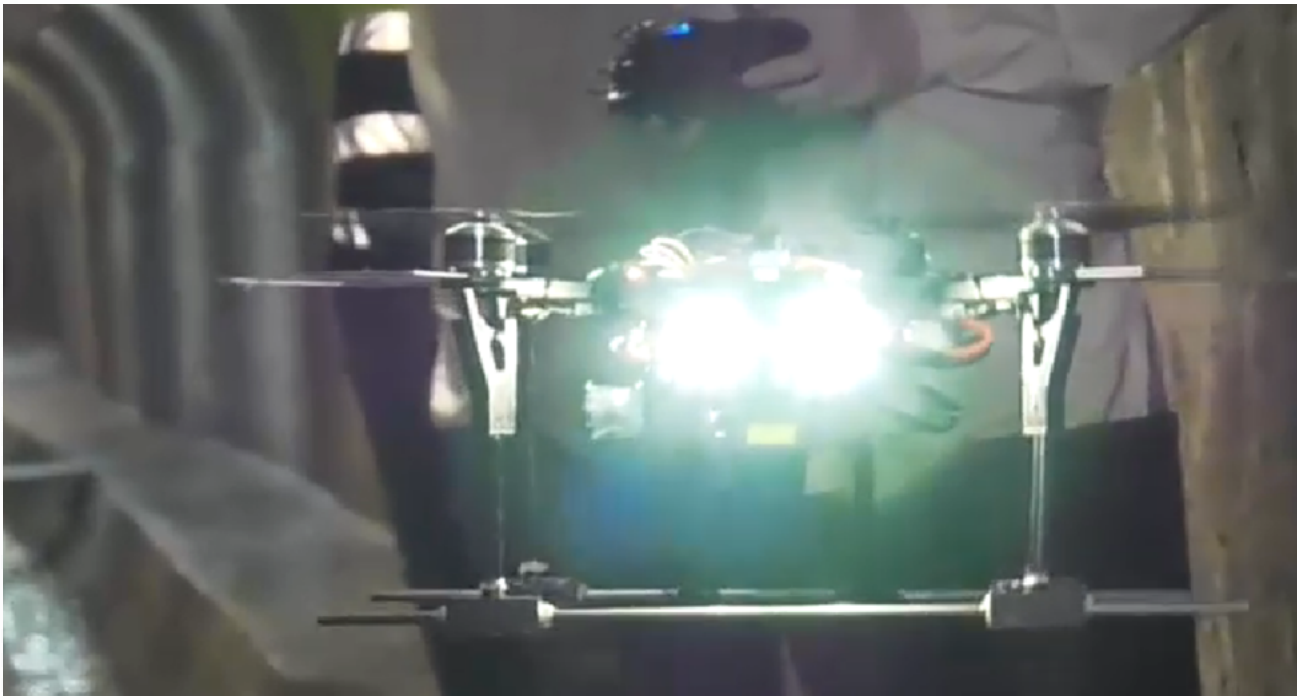
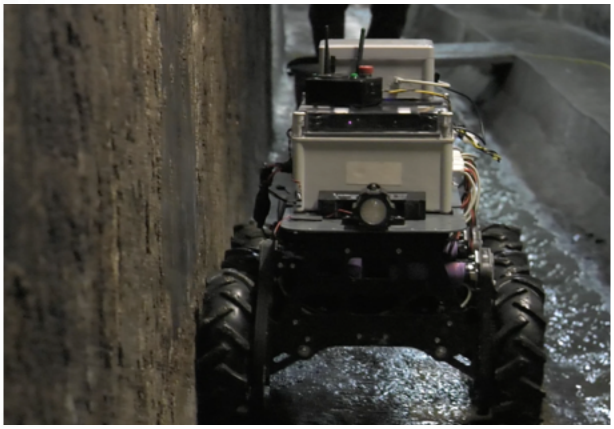


FIG. 15B



A number of companies have begun to enter this space. This includes companies such as ***Echord***, which has developed both an aerial robot (ARSI) (Fig. 15A) and a ground robot (SIAR) (Fig. 15B) that inspect sewers with minimal human intervention.[33] ***Teleretail*** is a firm developing urban logistics robots capable of providing deliveries to citizens of smart cities without the need of a human operator (Fig. 15C, 15D).[34] These robots are solar powered and capable of traveling almost unlimited distances. Further improvements may lower the cost of these robots while increasing their safety.

FIG. 15C

FIG. 15D

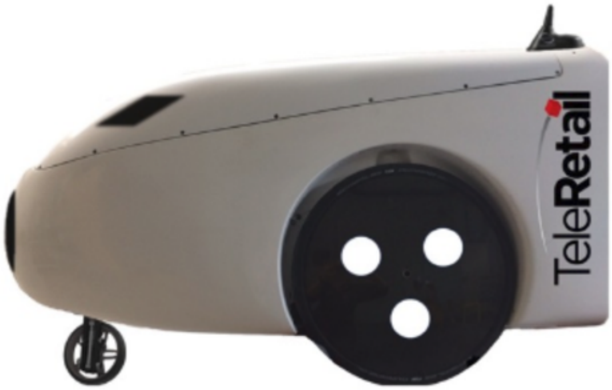


FIG. 16A

The Urban Robotics Lab has developed additional applications for drones working in urban centers. For example, they have developed a prototype aerial drone capable of repairing the windows of skyscrapers without human intervention (Fig. 16A), drones that can fight fires (Fig. 16B), and drones that clean green algae from bodies of water (Fig. 16C, 16D).[35] The application of these robots may free up enormous quantities of labor from maintenance tasks while allowing a city to perform preventative maintenance and ultimately run more efficiently.

THE APPLICATION OF THESE ROBOTS MAY FREE UP ENORMOUS QUANTITIES OF LABOR FROM MAINTENANCE TASKS WHILE ALLOWING A CITY TO PERFORM PREVENTATIVE MAINTENANCE AND ULTIMATELY RUN MORE EFFICIENTLY.

FIG. 16B

FIG. 16C

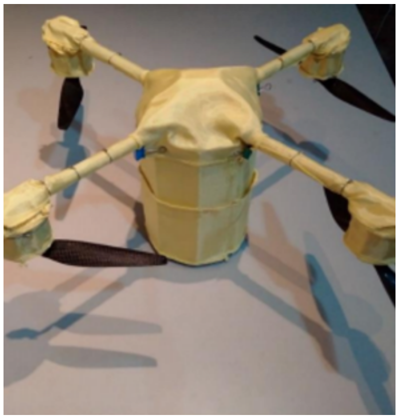


FIG. 16D

RESOURCE HARVESTING

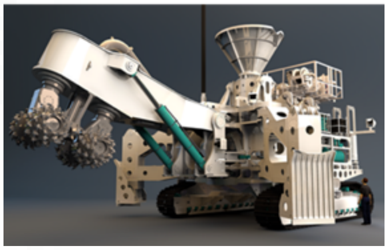
The collection of material from hostile environments is, theoretically, a wonderful use case for robots. Mining robots could allow for access to hostile environments without putting human lives at risk and may also be able to detect resources such as veins of ore that a human eye might otherwise miss. Robots are already being deployed by companies such as ***SMS Equipment***, which announced in 2018 that they will implement autonomous haulage systems at their company-operated mines and deploy over 150 autonomous haul trucks over the next 6 years (Fig. 17A). In terms of harvesting from more inaccessible environments, the Canadian startup ***Nautilus Minerals*** has developed a number of mining drones that are designed to work in deep-sea environments (Fig. 17B).[36] They are the only company to date to pursue setting up a deep-sea mine, but it remains to be seen if this will be a commercial success as they have faced financial difficulties recently.[37]

Another potentially valuable use of robots in this space is deep-sea exploration and harvesting of biomass for scientific study or the creation of new compound libraries for drug development. ***Deep Green and Nauru Ocean Resources Inc.*** are taking a slightly different approach; they are developing technology that will allow them to detect and collect polymetallic nodules on the ocean floor using advanced imaging and undersea drones.[38] ***The Wood and***

FIG. 17A

FIG. 17B

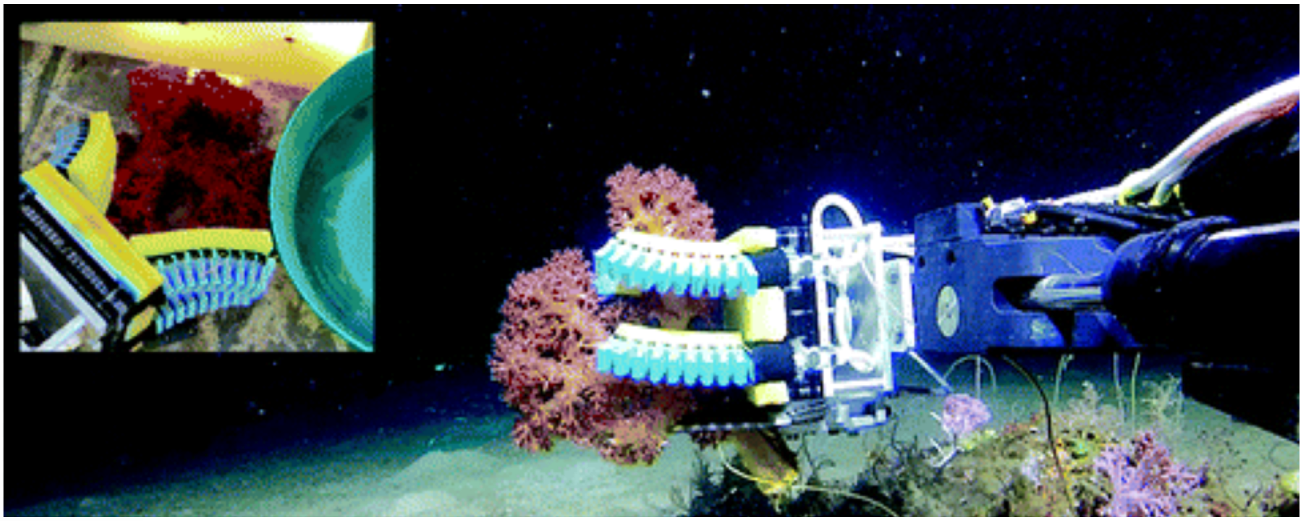
AUXILLARY CUTTER



BULK CUTTER

COLLECTING MACHINE

FIG. 17C



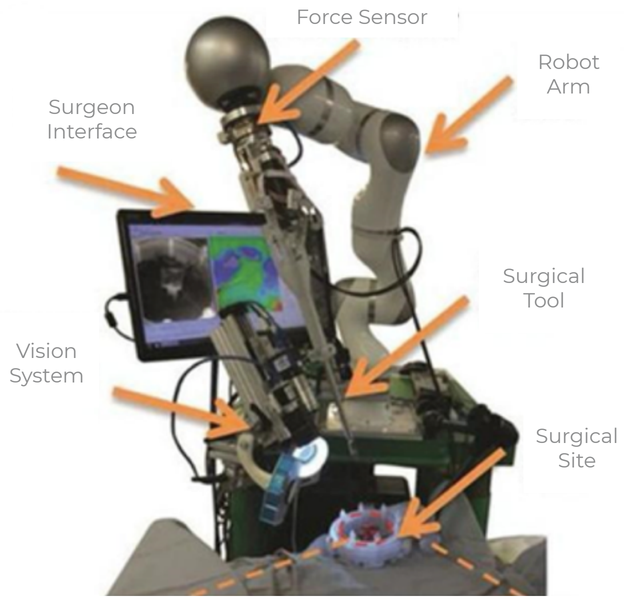
Gruber laboratories have collaborated to make a soft robotic gripper that can operate in the deep sea (Fig. 17C) for gently harvesting biomass without destroying it.[39] As they mature, these technologies may open up vast amounts of undersea mineral wealth that may be necessary to fuel our continued production of electronics.

MEDICAL ROBOTS

There is a major labor shortage in healthcare,[40] and the demands on the industry will continue to increase as the population ages. One potential solution to this issue is to increase the productivity of healthcare workers with robotic assistance. This would necessarily require that the robots be developed with strict attention to safety. Several firms have developed robots that help healthcare workers achieve dramatically improved efficiency. For instance, ***Diligent Robotics***, utilizing the dynamic obstacle avoidance system developed by ***Fetch Robotics*** along with a manipulator arm, has developed a robotic nurse that can safely navigate a hospital while moving drugs or supplies around the hospital in response to doctor commands (Fig. 18A).[41] Advances in telemetry mediated remote surgery allow for high precision procedures to be performed by surgeons even if they cannot be at the hospital where the surgery is taking place. The Smart Tissue Autonomous Robot ***developed at Children's National*** (Fig. 18B)[42] represents one of the first robots capable of performing surgery on soft tissue, allowing surgeons to work much more efficiently and with less fatigue. These and other advances will help address the looming labor shortages facing healthcare; decreasing the heavy strain and burnout which facing the medical workforce.[43]

FIG. 18A

FIG. 18B



CONCLUSIONS

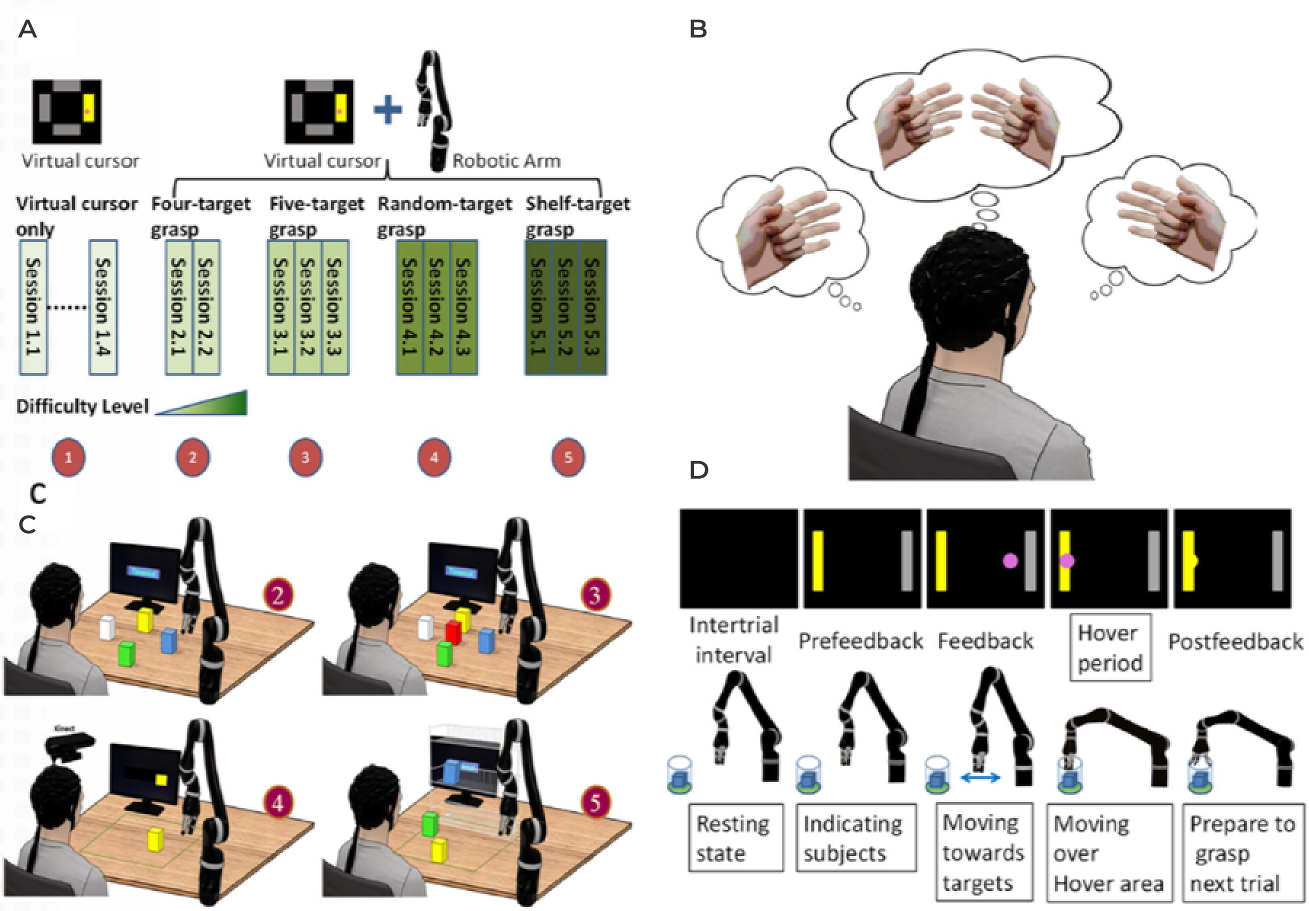
The next generation of applications for robots is being made possible, in part, by advances in safety and sensing technologies. Improvement in the cost/benefit ratio of using these robots will depend upon the cost-effectiveness of their sensors, the ease of their control, and their autonomy. Currently, many robots are designed to either perform very simple tasks such as moving objects from one place to another while dynamically avoiding humans or perform a series of preprogrammed tasks in a clean room with little to no variation in inputs. Developing more robust control mechanisms and sensor suites will allow robots to perform more complex tasks in concert with humans in a high-variation environment. Accomplishing this will allow one expert worker to control one robot intuitively, and may eventually allow them to coordinate suites of robots working in concert while benefiting from the operator's domain knowledge to rapidly accomplish a series of tasks. This will allow industries to utilize the human individual's expertise as broadly and efficiently as possible.

4 The Next Frontier of Human Machine Collaboration: Communication Efficiency

INTRODUCTION

There is a skills shortage in the workforce, particularly in sectors where technology is changing rapidly such as manufacturing, advanced technology, and health. As robots become capable of performing more tasks in these settings, there will be a temptation to pivot to training computer technicians and robotics engineers and expecting them to replace workers with domain expertise. These technical positions will be important, but requiring the operators of all robots on a factory floor to be highly trained engineers would be impractical at best. Further, having a modular factory without the presence of skilled artisans would go against one of the core concepts that makes the strategy outlined in The Toyota Way so successful: trained experts who are empowered to stop the line and propose or implement improvements are extremely valuable. If robots are to empower these trained experts to work more efficiently while maintaining their expertise, controlling the robots and teaching them must become as intuitive as driving a car or teaching an apprentice. In this section we will describe the current state of the art in direct information transfer between humans and machines, current applications in this space, and the advances that must occur to bring this technology from the laboratory to the factory.

FIG. 19A



THE STATE OF THE ART OF HUMAN MACHINE INTERACTIONS

The current mode of human-machine interaction follows some familiar modes. The most technically challenging forms of control are done through programming, which requires explicit programming expertise. In most industrial settings, robots are instead controlled through a graphical user interface (GUI) and some iteration of joystick/controller. Advances in GUI have focused on making the control of robot behavior as simple as possible. However, even with these simplified user interfaces, inexperienced users will still struggle with failures in robot interaction.[44] Movement away from classical control paradigms may improve the ability of industrial domain experts to work alongside robots more intuitively, decreasing the rate of expensive errors and increasing productivity.

NONINVASIVE BRAIN-MACHINE INTERFACE

While direct brain interfaces produce a relatively clean signal from a small number of neurons, the surgery required for this method makes it impractical for more broad applications. An alternative is to use a series of wearable sensors to measure brain activity through noninvasive electroencephalography. These sensors, which can be worn as a skullcap, can detect, report, and quantify brain signals. These signals can in turn be used as outputs that can be used to control machines. This process takes some practice but can allow a user to direct a machine just with their thoughts, theoretically freeing their hands for other tasks. For example, the ***Ben He Laboratory at the University of Minnesota*** has published studies showing that users wearing these noninvasive sensors can control a robotic arm (Fig. 19A). The lab developed a method for training users to use the interface by moving a cursor on a screen just with the noninvasive electroencephalography interface, but still found that after a number of sessions the participants could not move blocks through 3D space at a theoretical speed with no redundancy or hovering (Fig. 19B).[45] In further research, the He laboratory found that the combination of overt spatial attention and motor imagery, using two measures as opposed to only motor imagery (Fig. 19C), could dramatically improve the ability of subjects to robustly control the cursor in 3D movement tasks (Fig. 19D), resulting in an average information transfer rate of about 30 bits per minute.[46] These results suggest that while noninvasive brain scans can allow for effective control of robots, the addition of other modes of control can dramatically improve the efficacy of a human pilot.

FIG. 19B

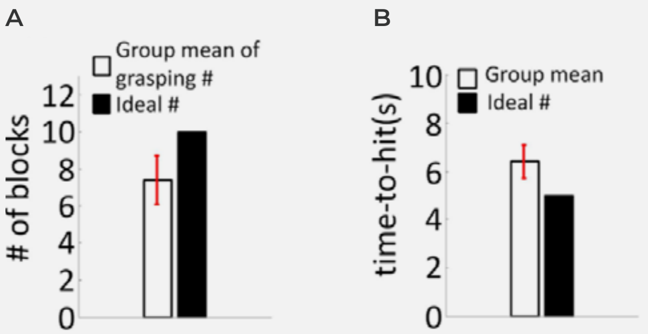


FIG. 19C

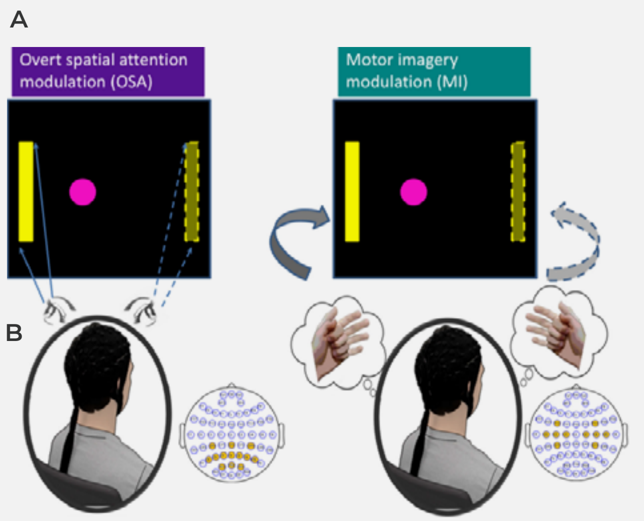
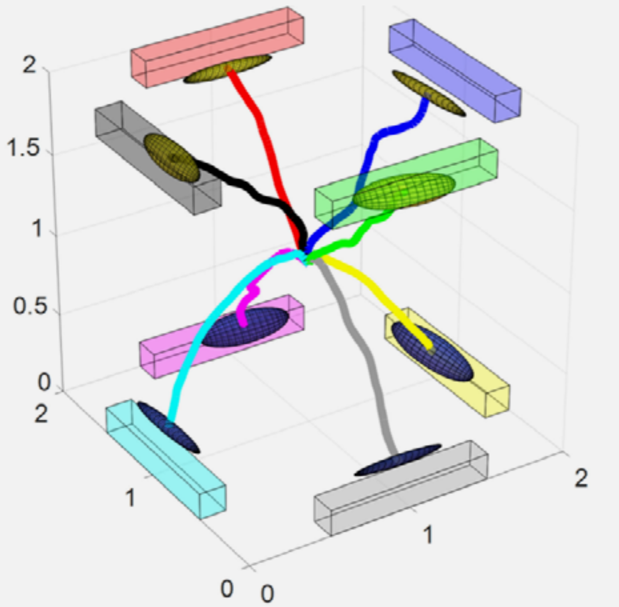


FIG. 19D



NONINVASIVE BODY-MACHINE INTERFACE

Control of robots by noninvasive EEG requires a significant amount of practice and is somewhat unintuitive. Historically, this technology has been developed to help people who are paralyzed interact with the world. In this case, speed, scalability, and rapid training time are less essential. However, the need for hesitation and recollecting one's bearings is not necessarily appropriate for industrial applications. By using sensors attached to parts of the body we normally use for grasping or moving, we may abrogate the need for such extensive training and create a more intuitive machine control interface.

FIG. 20A

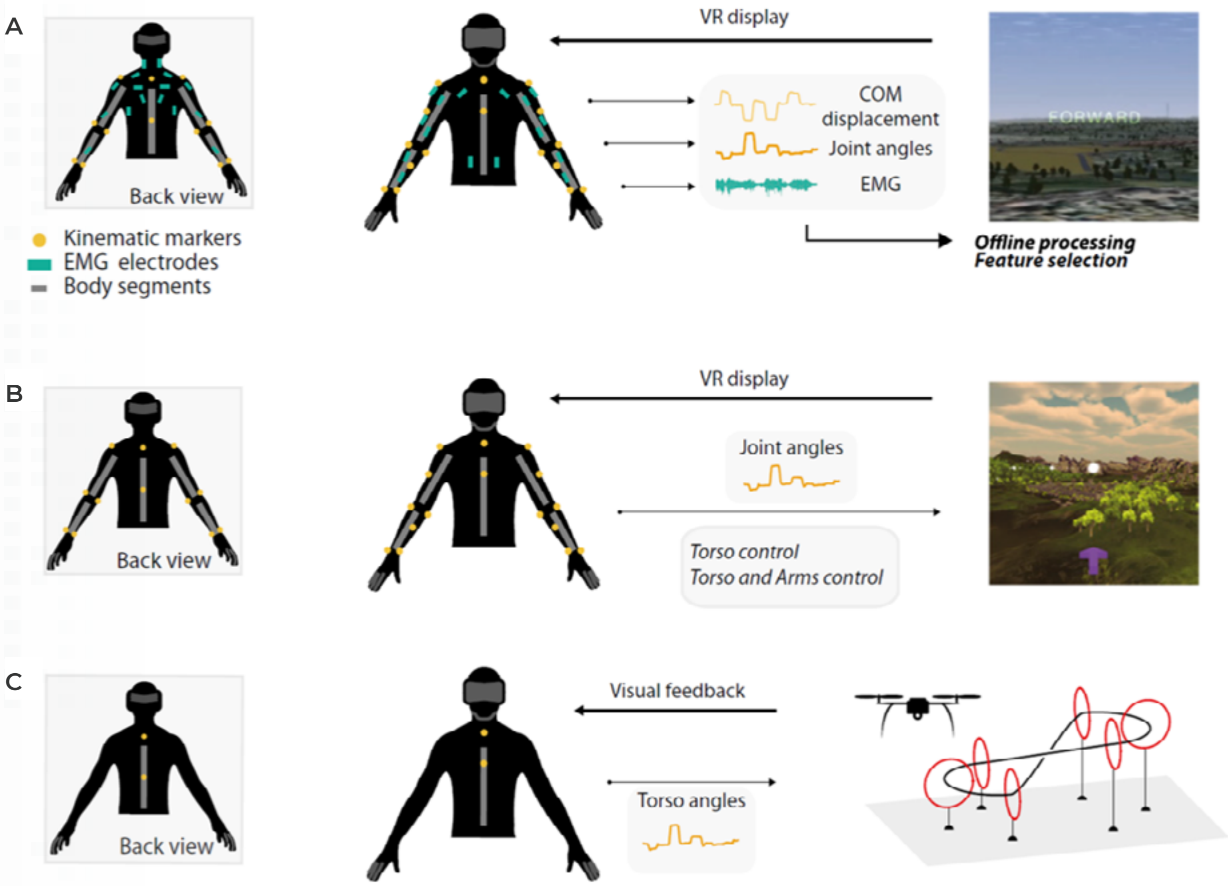


FIG. 20B

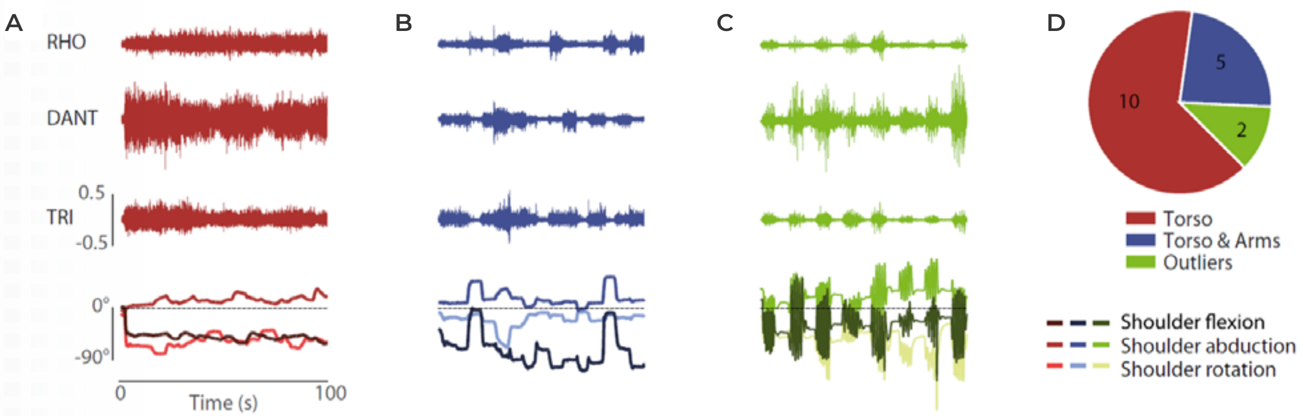
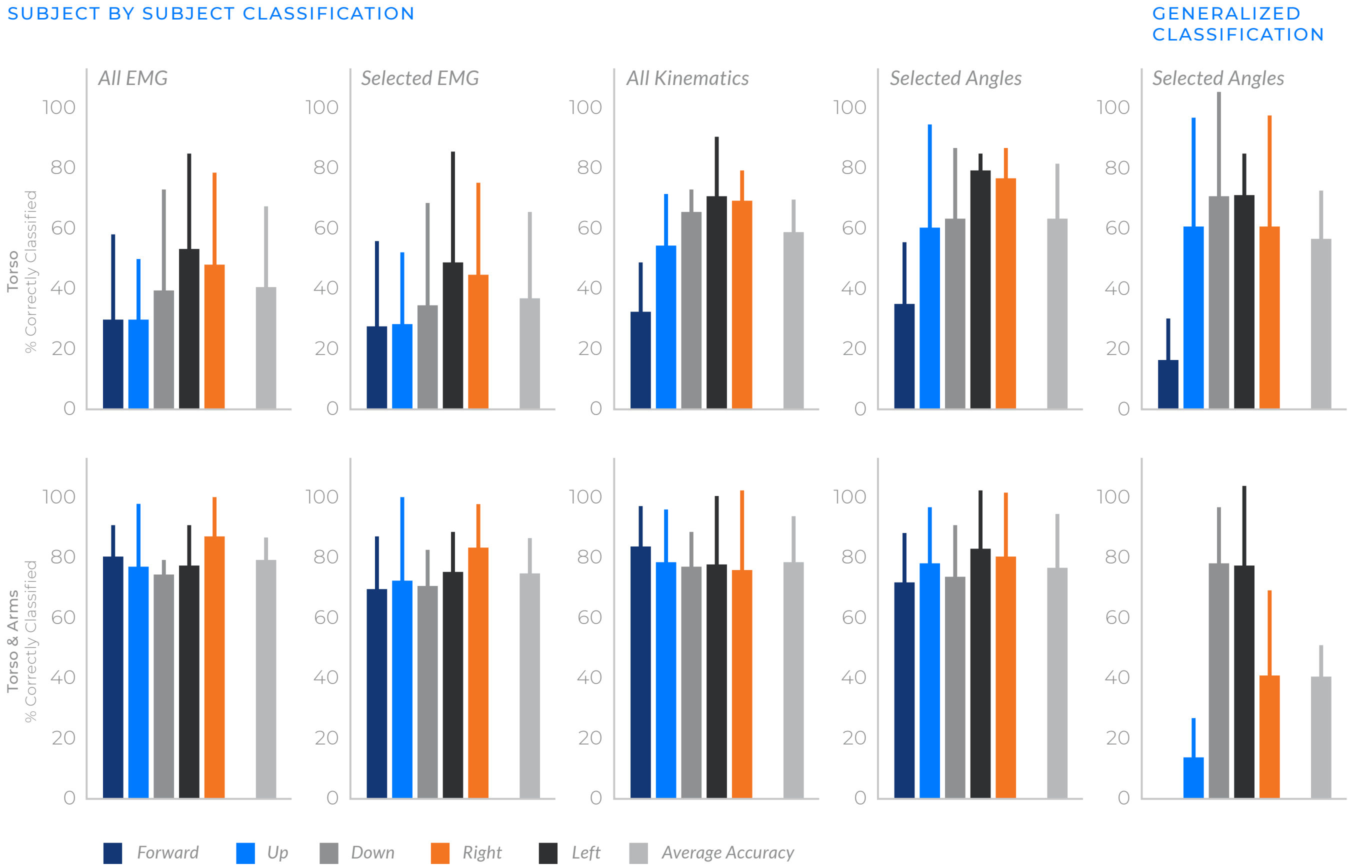
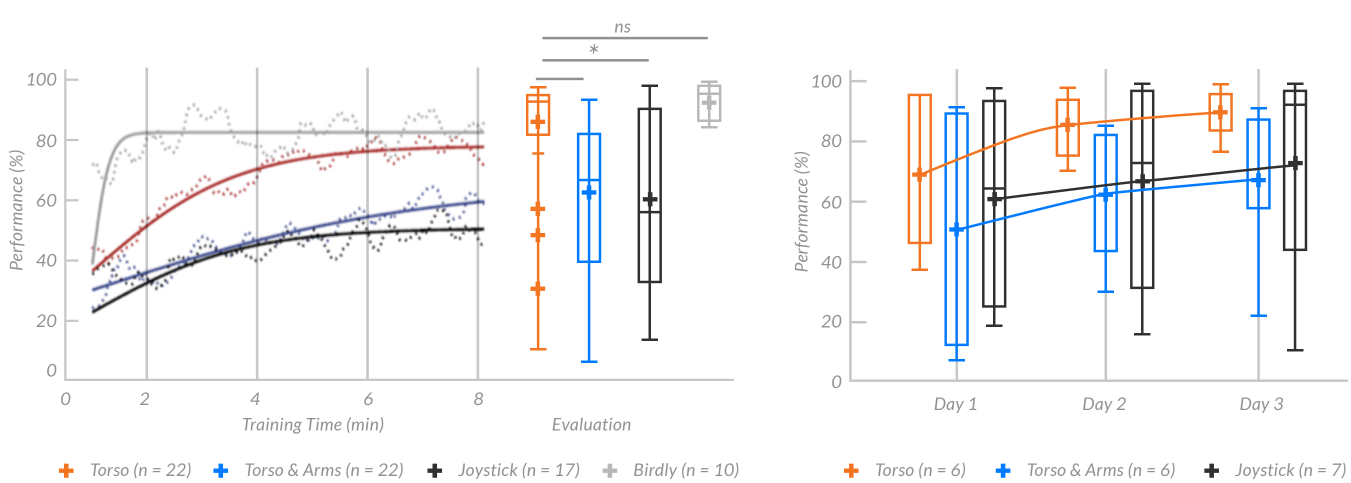


FIG. 20C



For example, the ***Micera Laboratory*** has developed a body-machine interface for the control of airborne drones that allow an operator to rapidly fly the robot through an obstacle course using intuitive body motions. Their sensor suite includes kinematic markers and EMG electrodes and allows the user to see through the drone's eyes using a VR set (Fig. 20A).[47] Using a series of sensors, the movement of specific muscles can be turned into extremely precise signals that can be used to communicate commands to robots, particularly when combining torso and arm movements (Fig. 20B, 20C). Interestingly, the Micera Laboratory used a suite of these sensors to allow subjects to control the flying drone as if they were a bird, using their arms and torso to direct the flight. This command structure allowed subjects to control the drone with less than a minute of training time, while subjects using a joystick took 8 minutes to achieve 20% less performance than the group controlling the drone by sensor (Fig. 20D).

FIG. 20D



The EPFL laboratory, led by professor Dario Floreano, has developed an exosuit that allows for the control of a flying drone in a similar fashion. This "flyjacket" comes with a number of sensors attached to the suit, a smart glove with sensors to detect hand motions, and a VR set to produce a body-machine interface for natural control of a drone (Fig. 21A).[48] The sensor outfit is also adjustable to a range of body sizes (Fig. 21B). The support and sensors provided by the flyjacket demonstrated dramatically improved values for RMS error and variance relative to joystick control in both clear and cluttered environments (Fig. 21C, 21D). Neither of these body-machine interface systems are commercially available at this time, but they represent near-commercial scale work being done by Universities.

While these body-machine interface systems have been primarily investigated for flight and direct teleoperation, it should be noted that the robust and specific data outputs from these systems can have a range of applications. Similar suits could be used to control an industrial robot or train an industrial robot to perform a range of context-dependent tasks with high precision. As our ability to incorporate multiple types of input increases, so too does the scope of tasks that can be performed by robots.

FIG. 22A

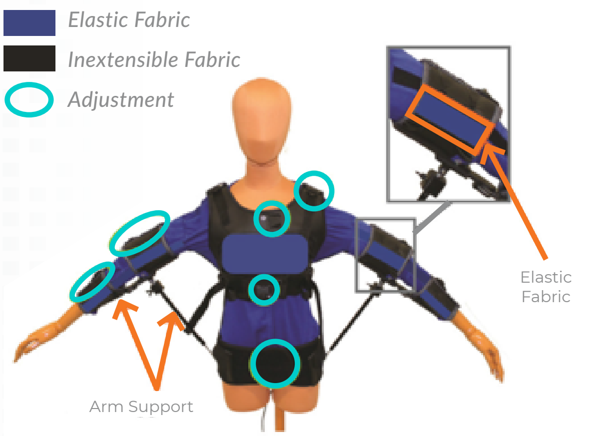
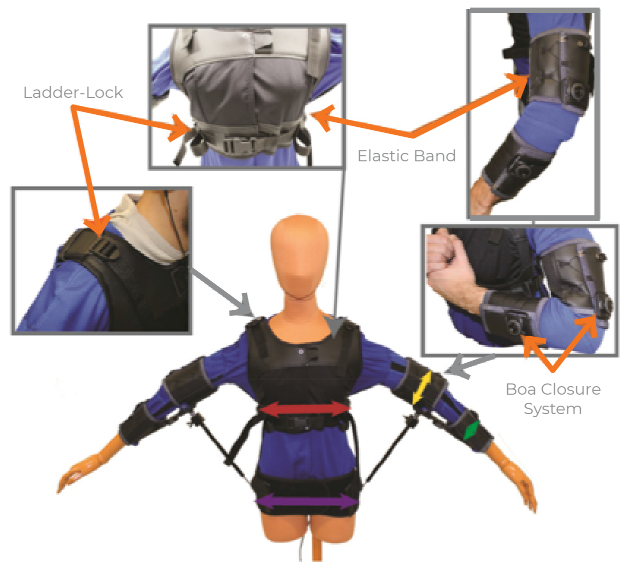


FIG. 22B



Body Region	Minimum Diameter (mm)	Maximum Diameter (mm)
Forearm	180	300
Arm	220	360
Torso	680	1100
Hips	730	940*

**additional fabric with velcro can increase the maximum diameter*

FIG. 21C

IN OPEN ENVIRONMENT / n = 8

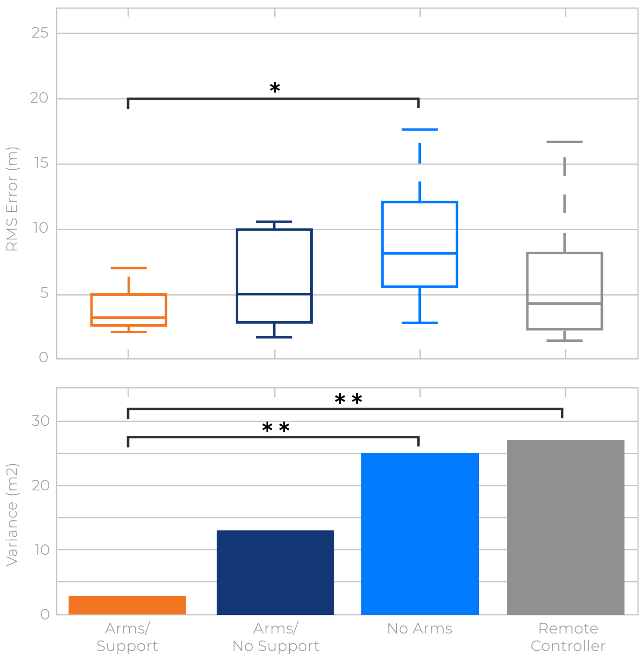
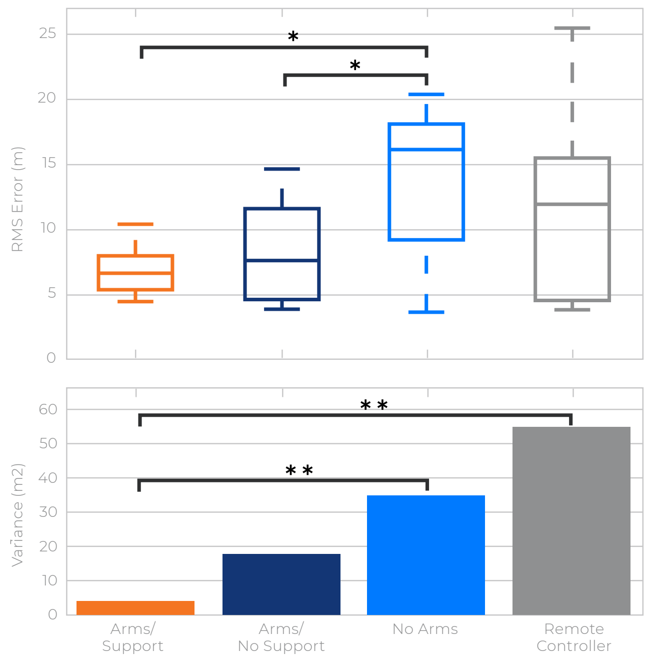


FIG. 21D

IN CLUTTERED ENVIRONMENT / n = 8



BRAIN SWARM INTERFACE

There are some large-scale tasks such as agricultural labor that would greatly benefit from coordinated drone swarm behavior; however, this paradigm cannot be managed with traditional controls and would be a challenge to manage even with the control systems provided in body-machine interface sensor suites. ***The Schwager Group at Stanford University*** has combined two types of inputs, eye tracking and an EEG headset, to permit the simulated control of a 128-member robot swarm (Fig. 22A).[49] In this system, the location of the drone swarm was controlled by detecting eye movement, and the density of the swarm was controlled by EEG interpretation. While the swarm could be controlled in physical space with this combination approach, there was significant variance in drone movement even when just controlling three drones (Fig. 22B).

FIG. 22A

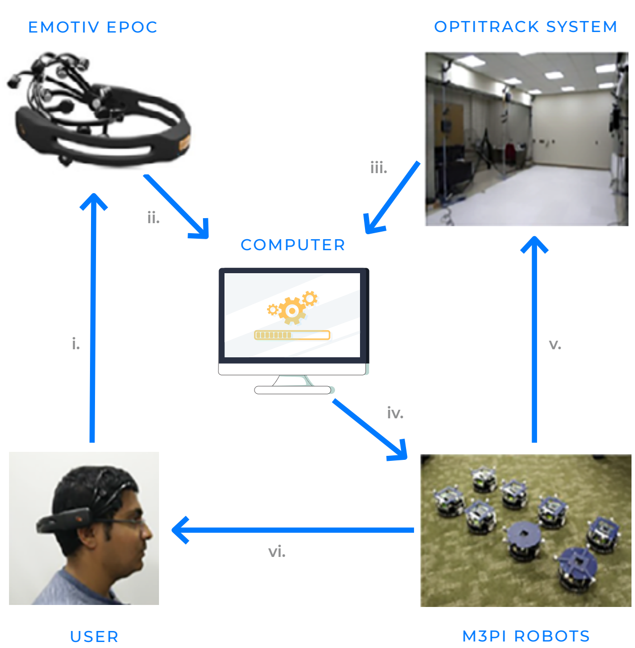
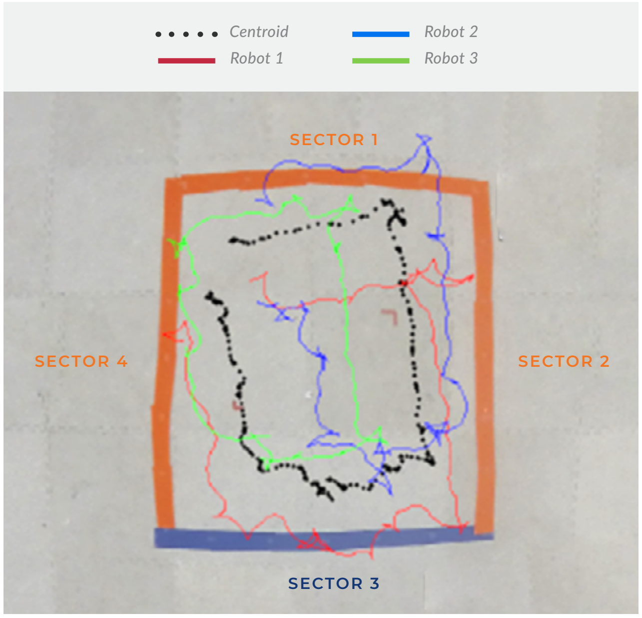


FIG. 22B



Along these same lines, ***the Lennox Lab at the University of Manchester*** has developed a human-swarm interface focused around letting a human operator control the actions of a swarm of robots using a VR interface. Their hypothesis was that by moving the robots as if they were an omnipotent virtual giant (Fig. 23A) with a combination of gestures picked up by a VR helmet (Fig. 23B), a human operator would be able to more easily handle the incredible complexity of handling a drone swarm. In their recent paper, the Lennox Lab demonstrated the ability of this interface to allow humans to, with minimal training, control the movement of multiple drones at once (Fig. 23C).[50]

It may well be that as the sensitivity of EEG, machine vision, and control algorithms improve, the control demonstrated by these systems may improve as well. These proof of concept studies also suggest that the combination of eye tracking and human machine interface may permit higher-precision drone control and the effective use of drone swarms for industrial applications.

CONCLUSIONS

The research driving advances in directly interfacing with machines is still largely in the basic research stage at select universities. As this field matures and companies are spun out of academic groups, it will be important to evaluate the training time for a user to achieve proficiency as well as accuracy with a particular tool set against the cost of implementing the tool. The next great innovation will be to incorporate machine learning and computer vision to help decode the actions and intent of a user with as much precision as possible. Ideally, the machine learning system will allow robots to work with an operator to further refine the signal-to-action relationship.

As this process becomes more refined and natural, the operation of robots will require less formal training. This may in turn dramatically increase the productivity of the workers by allowing them to focus on the task at hand, with a little help from their friends.

FIG. 23A

FIG. 1. THE SYSTEM ARCHITECTURE OF THE PROPOSED HUMAN-SWARM INTERACTION USING *OMNIPOTENT VIRTUAL GIANT*

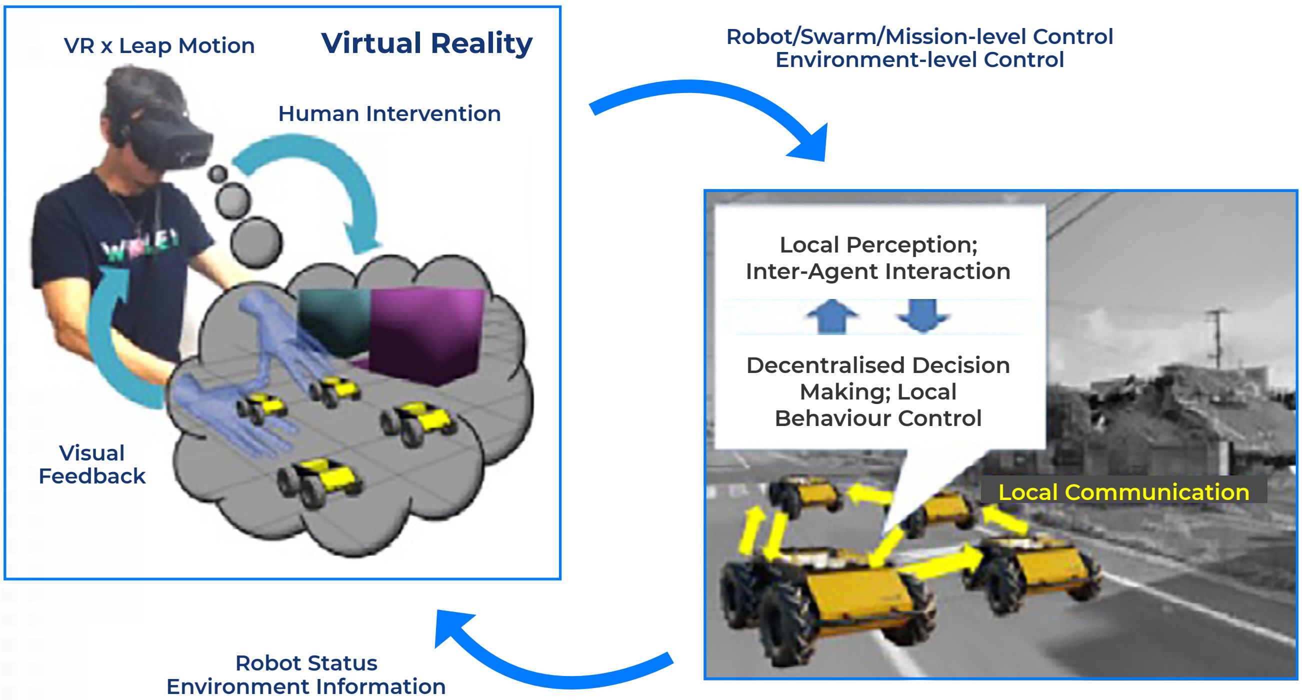
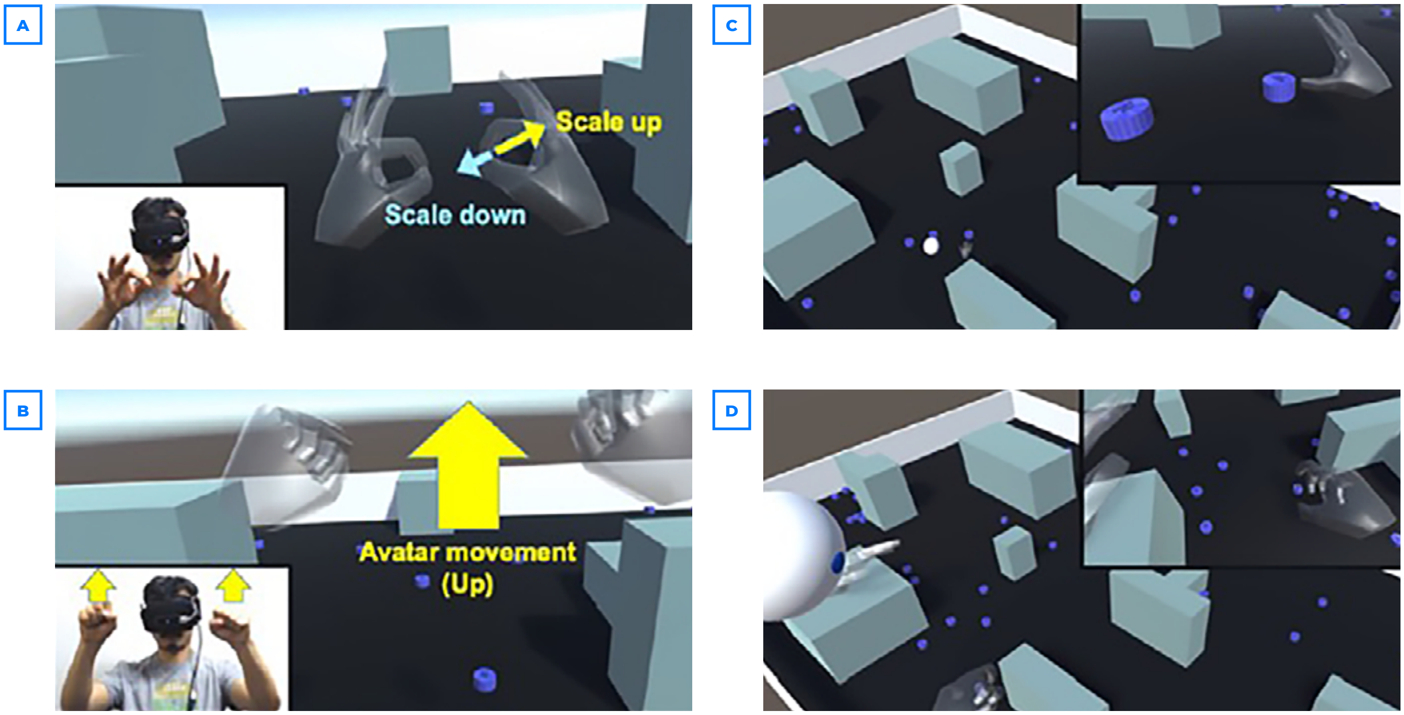


FIG. 23B

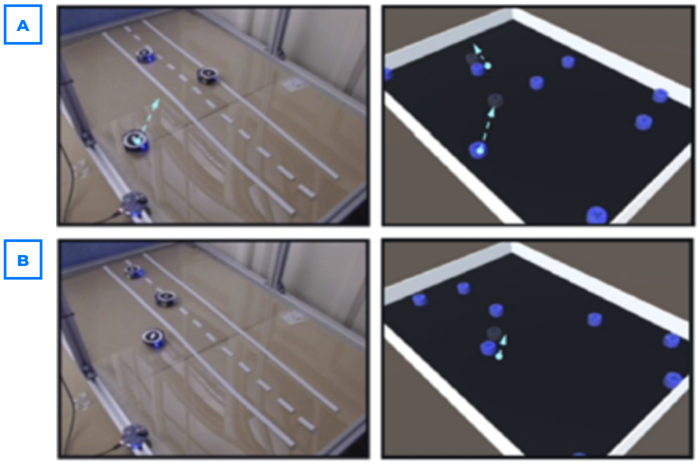
PERCEPTION INTERFACES



(a) resizing the world; (b) flying like Superman. Using the interfaces, a user can have (c) an ordinary perception, or (d) macroscopic perception for which the avatar becomes a virtual giant. In (c) and (d), the white oval object indicates the avatar's head, and the upper-righthand subfigures show the user's view.

FIG. 23C

EXPERIMENTAL VALIDATION OF THE PICK-AND-PLACE INTERFACE



(a) once the holographic objects of robots are relocated, (b) the real robots move towards them. The left subfigures show the real robots, and the right subfigures show their visualisation in the virtual space and the other virtual robots. The dashed arrows indicate the remaining journey to the target objects.

THIS MAY IN TURN DRAMATICALLY INCREASE THE PRODUCTIVITY OF THE WORKERS BY ALLOWING THEM TO FOCUS ON THE TASK AT HAND, WITH A LITTLE HELP FROM THEIR FRIENDS.

Interview with Carl Vause, CEO of Soft Robotics

Where do you see the future of robotics moving in the next 5 to 10 years?

The next major advancement in robotics is going to be overcoming the variation barrier. Robots are very good at welding cars and palletizing boxes, but it is difficult for them to operate in environments which have high variation. In many respects, variation is the enemy of robotics. There have been decades of research that have gone into solving this problem. Some potential and very complex solutions which have been explored include the development of hugely complicated algorithms and machine vision. There has also been a great deal of work done in developing complicated grasping mechanisms.

The need for robots which can work well in a high-variation environment is very real and is receiving very little press right now. This is particularly important for consumer-driven manufacturing strategies. Before we got into the omni channel world, customers would go into a store and pick between a set number of options on the shelf. Manufacturers could do relatively straightforward SKU optimization, figure out what product was the most profitable, and focus on making that exclusively. Companies could then spend a great deal of time optimizing out their manufacturing line to make as few of a given item per batch as possible.

With the advent of online shopping, the consumer has all of the power. If they don't want the item you have on a shelf, they will leave and find the thing they are looking for. This has led to manufacturing de-leaning, or SKU proliferation. We know some companies are talking about on-demand manufacturing: a single SKU for a single customer, if you will.

Companies are turning to automation to solve this problem. If I am a consumer goods company, I am stuck manufacturing all of these proliferating SKUs for different channels, segments, consumers, and clients. These manufacturing facilities are so-called unstructured or low-structure environments, and they are where things are starting to turn, as traditional automation is ill-equipped to handle these environments. This is where technologies enabling automation which can accommodate variability will be so important.

Traditionally, automotive and electronics have represented 75% of all robot sales. Robots are very good at welding and are very bad at accommodating new shampoo bottle shapes for holiday promotions. We have seen the robotics market dominated by automotive and electronics and what we call "general industry." In the robotics field, we joke that general industry is anything not automotive.

With new technologies like soft robotics and collaborative robotics, you are starting to see robotics penetrate into new markets like the food industry in multiple vertical segments including farming, supply chain, and grocery delivery. If you look at what Kroger is doing, you can see that they are spending hundreds of millions of dollars on grocery delivery automation. These advancements are really changing the use case, and that is really where the majority of robotics will be moving forward, bringing automation into industries such as consumer goods, where you have high variation in items like shampoo and bottles of toothpaste. For example, cosmetics is a space where there is an incredible amount of variation; it has very fast product cycles. Logistics robots may be able to deliver goods right to your door, but only if they are able to efficiently handle a high-complexity environment.

Right now the process by which food gets to your table is highly manual, and this is a problem because of labor scarcity. In the food space, there is also an enormous degree of variability. We really need to figure this out because the SKU proliferation genie is not going back into the bottle; the consumer isn't just going to wake up one day and decide they want to go back to a choice of six.

There is a classic axiom in automation which is that the more heavily roboticized your factory is, the more difficult and expensive it is to retool the factory. How do you feel this concept will be challenged moving forward?

Moving forward, how do I build a factory that I can rapidly and economically retool is a hugely important question.

How do you see robotics changing in spaces where, right now, it does not have much exposure; for instance, healthcare and urban robotics?

I think there is a paradox that is interesting. These industries constantly say that they are under pressure. And technology is advancing in such a way that they should be rapidly moving towards adoption. What they are seeing, however, is that these industries are not rapidly adopting robotics; in fact, they are often not even piloting.

I am in a working group; what we have found is that often, the burden of the manufacturing process is on the manufacturing organization. They are often resistant to allocating sufficient funds to make the pilot a success.

So you have these innovation teams, and these innovation teams test out and see technology. But they will not be able to buy or deploy the technology. What we see with the outlier companies who are quickly adopting new technologies is that the initiative is driven from the top. Some groups are kind of hoping that this process will bubble up from the bottom, but this does not work. Instead, it leads to a never-ending cycle of piloting and testing and the great leap to production does not wind up happening.

Given this, what do you feel are best practices for incorporating advances in robotics into your manufacturing process?

From what I have seen, the companies which are most successful with this are those which have a senior executive sponsor the automation initiative who reports to either the CTO or the CEO. Some of these successful companies have a chief digitization officer or someone else at the C level. Companies which have made automation part of their strategy from the top, with an accountable senior executive executing on this, are generally outliers that are well ahead of their peers. Unfortunately, when manufacturing engineers try to tackle this challenge, they often don't have the time and ability to deploy and start up the new technology.

Another reason why we are not seeing so much uptake: This is a journey. I often talk to customers; in the 90s we were rolling out ERP systems. Starting up Oracle or PeopleSoft or similar systems was not a fun experience, but we could not imagine, now, running our systems without it. You look back now and say, my gosh, if we didn't start up an SAP 10 or 20 years ago, where would we be?

This is exactly where we are with robotic automation today. It's a journey. If you know it is a journey, you can test your adoption of automation and robotics through setting clear milestones with clear metrics and say, if we hit this milestone on enterprise adoption, then we can move forward.

Do you see any specific technological challenges which are preventing adoption of robotics in some of these general industries, and do you see them being overcome in the next 5 to 10 years?

We deal with the grasping problem; once you make a good grasper, you can go full bore. We are deployed today with customers around the world, and things are moving in the right direction. It is largely about making people aware that this is something they can do. Often, people are just not aware that there is a solution out there.

In the case of autonomous mobile robots, you will see increased adoption because the price of LiDAR is coming down. I think that is very interesting.

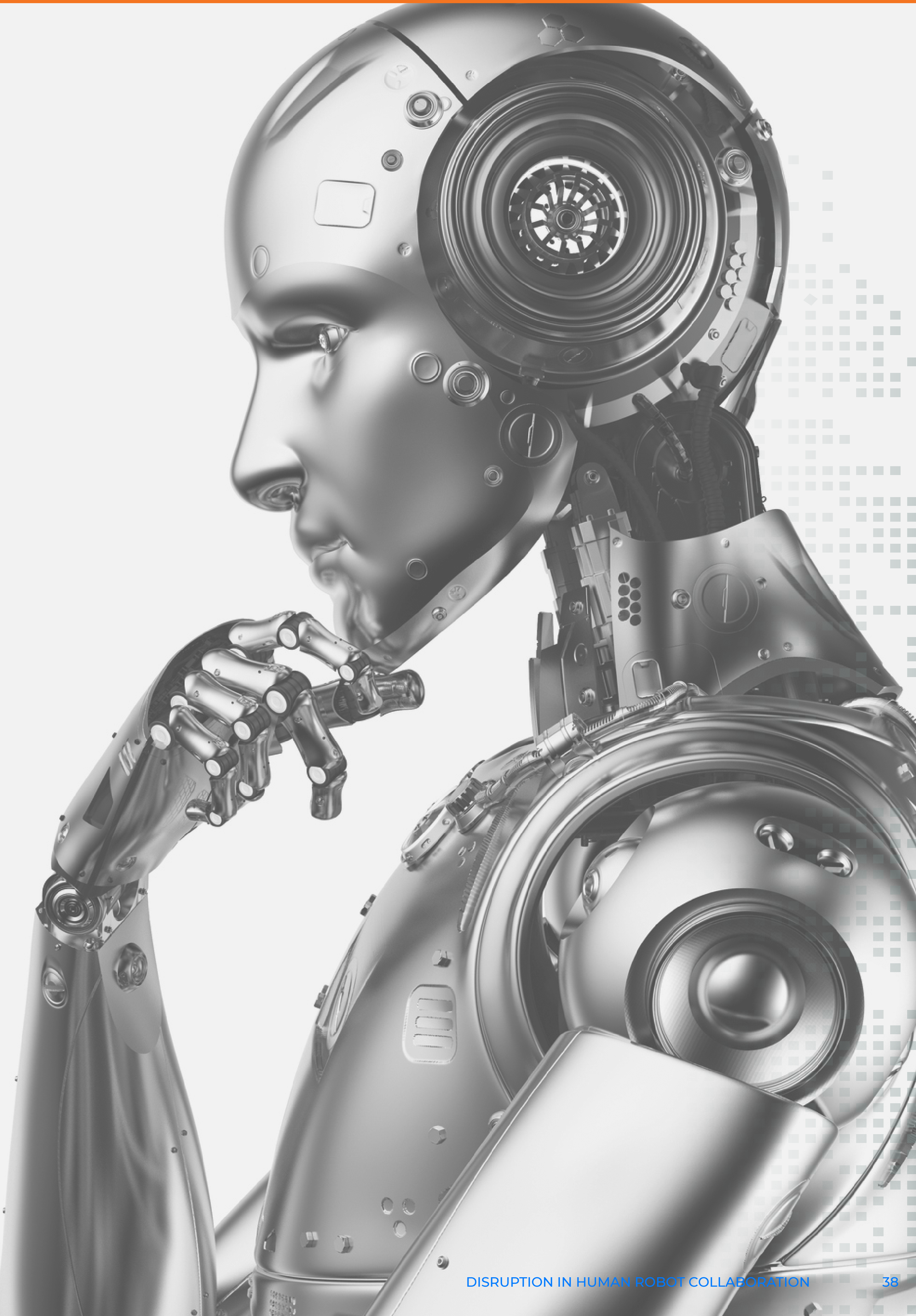
A big part of the technological challenge is grasping. I think that there is a big challenge in ease of use for automation. Solutions in this space will facilitate the development of truly collaborative robots and some of the bigger solutions like autonomous mobile robots.

Are there any particular enabling technologies in the collaborative robot space which are particularly exciting right now?

The Universal Robot is kind of the big one which has enabled ease of use. Being able to use it out of the box, where you don't have to go away to a special school to learn how to program it. It has a touch screen, where you don't need more than a very basic mechanical background to immediately start using it. With collaborative robots, ease of use, ease of setup, and ease of programming are very important things.

Moving forward, how do you see your company's technology developing?

Traditionally, we have worked on bringing agility and adaptability to industrial robots. Additionally, we are now doing a lot of work in the collaborative space. These are customers who want ease of use, changeovers, and rapid redeployment of their robots. Our technology facilitates this. The dream is to have a robot which can drive around and grab things. Now, a robot which can only drive around and pick up one item at a time is not very valuable to you, so we are working on making these robots more efficient and capable of picking up a broad range of SKUs. We are starting to marry our technology to mobile robots that have arms on them to make this a reality.



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