Cobot Safety Features Implemented for Manufacturing

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Abstract—Over the past two decades, the use of collaborative robots (cobots) have made an appearance in the manufacturing world. As cobots interact closer with humans in assembly lines, precautionary measures are being taken to ensure the safety of the operators who work alongside them. In such interactions, cobots have to analyze the stimuli in their surroundings in order to predict, prevent, and respond to safety hazards. Common safety features added on to cobots can include depth cameras and animated faces. These safety features allow cobots to adapt to their environment while optimizing their performance alongside humans. This paper establishes the importance of adding safety features to cobots and analyzes scenarios and research of such safety technology.

Key Words—animated faces, automation, cobots, depth cameras, sensors, worker safety

Revolutionizing the Manufacturing Sector

Since the rise of manufacturing, there have been several waves of revolution. First came steam engines and the first machines. From there, electricity, the assembly line, and mass production were born. The next wave brought computers and the start of automation when robots were first seen on the assembly line. Robots began appearing throughout the 1950s and 1960s. This has led up to the latest revolution in manufacturing.

McKinsey & Company reports that “Industry 4.0” is the term being given to this next wave in manufacturing. Industry 4.0 is characterized by addressing disruptions including that of focusing on improving and creating forms of human-machine interaction. The digital technologies being brought forth by Industry 4.0 have been in the works for some time. Some of the technologies are not ready to be implemented on a large scale, but may have reached a point where they are ready for industrial use due to a greater reliability and lower cost [1].

While Industry 4.0 is making available new technologies to help in the automotive and industry sectors, many manufacturing leaders are not “consistently aware of the emerging technologies” [2]. Only 48% of 300 manufacturing leaders surveyed in January 2015 considered themselves ready for Industry 4.0. Once manufacturing leaders do become aware of the technologies and begin to utilize them, they are sure to affect “every corner of the factory and supply chain” [2]. These emerging technologies often have the potential to increase sustainability in the manufacturing sector. A growing number of manufacturers are realizing the significant financial and environmental benefits that are a result of sustainable business practices. This paper will focus more on the financial benefits. The United States Environmental Protection Agency (EPA) includes in their definition of sustainable manufacturing the idea that it enhances employee, community, and product safety. The EPA goes on to state that one of the major reasons companies are pursuing sustainability is to “increase operation efficiency by reducing costs and waste” [3]. This paper focuses on the specific safety technology of collaborative robots (cobots). As this technology continues to develop, its applications and benefits continue to evolve and become more evident.

Cobots: What Are They and Where Do You See Them

Cobots are small, mobile robots that are designed to assist humans by alleviating or eliminating extraneous tasks previously performed by humans. Given that in every field of work humans can be stuck completing basic, repetitive tasks, cobots are applicable in a variety of environments. For example, cobots can be seen in manufacturing, warehousing, logistics, and healthcare [4]. The wide application of cobots is due to their affordability, ease of deployment, versatility in customization, and process improvement. Research conducted by MIT at a German BMW plant concluded that incorporating cobots into their assembly line decreased human idle time by 85% [4]. Not only do humans spend less time and energy on mundane tasks, but employers reap the benefits of faster production rates. Lead cobot manufacturers, like Universal Robots, only have three standard cobots on the market. One might conclude that one cobot from this supplier is no different from the next model. However, this is not true because each cobot completes a different task, in a different environment, and with different people, which is only feasible by customizing the cobot to these constraints. Additionally, there are a variety of cobot suppliers on the market, such as ABB, Epson, Festo, and Vecna. Each of these companies are producing products for a specific industry from aerospace to medicine.

Even though each cobot differs from the next, they do share some common similarities. More specifically in
manufacturing, cobots can be implemented to execute repetitive tasks, like screw driving, labeling, and quality control [4]. Due to the similarity of the tasks they complete, these cobots have similar structures. For tasks like the ones mentioned, cobots appear to have the same structure as a human arm. This contraption consists of a few joints to allow for articulate movements and rotation. Additionally, these cobots are lightweight machinery, therefore, they cannot work with high payloads. While this specific cobot would not be ideal for transporting heavy objects, the user could select a different cobot to meet this criterion. Not all cobots are designed the same, but they all are designed to aid humans in their jobs.

Industrial Robots

Industrial robots, large metal contraptions that spin and move items at fast speeds, repetitively, are usually the first prototype that someone visualizes when they think of robotic manufacturing. Industrial robots have been the primary resource available to the manufacturing world because they are ideal for systems that require high production rates, meaning that in order to achieve mass production, speed and accuracy are prioritized [5]. Such rates could never be replicated by humans due to physical limitations, like lifting abilities. Additionally, if such environments are not ideal for human labor, industrial robots can replace humans. By eliminating the presence of human labor, resources like lighting or conventional work hours are not necessary, only occasional monitoring of the system [5]. While this may prove to be more appealing to some manufacturers, completely removing human labor from the system is not the common trend in manufacturing. Robert Morris, vice president of a BMW plant, does not see human labor disappearing on the manufacturing floor when concluding that “ideas come from people, and a robot is never going to replace that” [6].

Industrial robots are being replaced by cobots in companies both with low and high labor costs. In 2010, Bajaj Auto became the first Indian automotive manufacturer to incorporate cobots into their assembly line. Bajaj Auto functions with relatively low labor costs and is now the world’s third largest motorcycle manufacturer. After testing cobots in a few different stages in their production process for three months, they were prepared to deploy the cobots “as a standardized solution for all of its functional requirements,” such as material handling. Bajaj later saw “zero annual maintenance costs and reduced power consumption”. They also reported that their employees felt like they were equipped with the tools to carry out their tasks with “faultless precision” [7]. Even given Bajaj Auto’s small budget, they were able to implement a sustainable solution to minimize labor intensive tasks performed by workers, while increasing productivity in their system, by using cobots.

Trading industrial robots for cobots, like Bajaj Auto did, is not a universal solution for manufacturing. As discussed above, cobots are ideal for human assistance, not to replace humans or industrial robots in every instance. Some cobots cannot meet the demands of the existing system. For example, Universal Robots, a Danish pioneer of cobots, sells three basic cobots that can work with payloads from three to ten kilograms [8]. If the system requires lifting an object of 15 kg, these cobots would not get the job done. This returns to the point that when cobots are incorporated so that the skills the cobots offer align with the demands of the system, efficiency and safety are improved.

In plants where human labor is still required, the presence of industrial robots can pose disadvantages to the efficiency of the production and the workers’ safety. These disadvantages also limit sustainability on the assembly line due to threatening worker safety as well as the ability to reduce costs. Due to their high speeds, ability to exert large amounts of force, and lack of spatial awareness, industrial robots pose as a safety threat to neighboring humans. As a precautionary measure, safety guards are placed, but do not always prove to prevent incidents. Here stems one of the main advantages of cobots over industrial robots.

NAVIGATING HAZARDS IN MANUFACTURING

Safety is an important part of any workplace, particularly when machines and technology are incorporate. Worker safety is vital because accidents, especially those that result in death, impact the lives of everyone. The employee’s friends and family will have to figure out how to live without that person in their life. The dynamics of the community and the workplace around the worker will be disrupted. Not to mention, when workers feel safer and more secure, distractions are removed that can affect their productivity [9].

Our research shows that robots in work environments tend to create concerns regarding safety. As mentioned previously, industrial robots are kept in cages away from workers in order to keep those workers safe. On occasion, workers have to go inside of the cages in order to perform maintenance on the robots. This is where safety concerns arise because in order to do their jobs, workers are putting themselves in danger. While safety protocols do exist in regard to robots, that they do not properly address a lot of the serious issues.

Current Protocol

The standard policy regarding safety concerns with robot maintenance is referred to as lockout/tagout. Lockout/tagout seeks to protect the worker by requiring hazardous energy sources to be removed when the machine requires maintenance. The hazardous energy source in an electric machine, like a robot, is usually considered to be the power source. Once the power source is disconnected, the next step is for a lock to be applied to the power source. A tag is then placed on the lock identifying the individual who put the lock
in place as the only person who can remove the lock [10]. Locks have “the individual worker’s name or other identification on it… [and] each worker has the only key to the lock” or set of locks [11].

The reasoning behind this is so the machine cannot be turned back on until the worker performing the maintenance work is finished. While this policy may seem easy enough to follow, issues arise because a lot of tasks regarding robot maintenance require power in the robot. For example, programming, setup, and troubleshooting all need power in order to be performed. According to Mike Taubitz, Senior Advisor for FDRSafety LLC, “in almost all cases, and this is something we’re slowly awakening to in the safety profession, these [robot related accidents] occur during the breakdowns, the nonscheduled, non-routine maintenance tasks” [10]. Since these accidents are unexpected, it is hard to address the safety concerns that arise because of them.

The other major concern with lockout/tagout protocol is that it does not enhance sustainability. Part of having sustainable business practices is being able to ensure both employee and product safety as mentioned previously. Employee safety cannot be guaranteed by lockout/tagout protocol considering this protocol has a lot of gaps in keeping employees safe when power to a robot cannot be shut off.

**Accident History**

In the United States, from 1984 to 2017, 39 robot-related accidents have occurred according to the Occupational Safety and Health Administration [12]. Twenty-seven of those incidents led to the death of a worker [10]. In Germany, which has the third highest per-capita robot deployment in the world, averaged three to 15 severe industrial accidents a year from 2005 to 2012 [13]. While this number only represents a fraction of all workplace deaths, 5,190 of which occurred in the U.S. in 2016 alone, robots should not be causing deaths to begin with [14]. Severe industrial accidents can be defined as those resulting in fatality or loss of limbs [13]. Several accidents caused by robots have occurred in the past couple of years.

In 2015, a 22-year-old man was crushed by a robot at a Volkswagen plant in Baunatal, Germany. The accident occurred while the man was “helping to put together the stationary robot that grabs and configures auto parts” [15]. He was grabbed by the robot and then pushed against a metal plate. The man died due to the injuries he sustained. Although Volkswagen does use lightweight robots that work alongside humans on the production line, the robot that crushed the 22-year-old was the type of robot that is usually kept inside a cage. In order to perform the proper maintenance, the man was inside the cage with the robot when he was grabbed [15]. About a month after the Volkswagen incident in Germany, a worker was killed by a robot in a car parts factory in India. Ramji Lal, a 24-year-old worker at a SKH Metals factory in Manesar, was stabbed in the abdomen while trying to adjust a metal sheet being welded by the robot. Lal was reportedly reaching behind the machine to adjust the dislodged metal sheet when the accident occurred [16].

The most recent incident of a worker being killed by a robot occurred in June 2016. Regina Elsea was two weeks from her wedding day when she was crushed to death by a robot while she was attempting to clear a sensor fault. Ajin USA, the company where Elsea worked, reportedly “encouraged line employees to get a stalled machine ‘back up and running as quickly as possible’” [17]. Besides encouraging employees to put themselves in dangerous situations for the sake of production, a slew of other issues, including lockout/tagout protocol not being followed, led to Elsea’s death [17]. While the robot was not the only factor leading to Elsea’s death, it can be argued that a robot requiring fewer steps in its accompanying safety protocol would prevent more deaths like this one by minimizing the room for human error.

**CURRENT SAFETY ADD-ONS FOR COBOTS**

Cobots, before any additional safety features are added on, are designed with characteristics that already promote safer interactions. For example, characteristics include smooth edges to prevent pinching and a lighter weight to decrease collision impact. While these standard attributes are beneficial, additional precautions that correlate to the specialized function of the cobot need to be taken. Depending on the customization the user chooses for the cobot, different safety features should be added. When interacting with humans, cobots have to be equipped with the appropriate technology in order to have the sensory abilities to predict, prevent, and respond to the safety hazards in its environment. Cobots can receive this sensory data through the addition of cameras and sensors. Furthermore, to aid the comfort and communication between cobots and humans, cobots can have attached screens displaying facial expressions. Each cobot will function differently from the next due to performing a different task or working with a different human. For this reason, cobots need to be prepared for a variety of situations through the addition of safety features.

**Cameras for Monitoring Hazards**

The technology of cameras is not a new innovation, but the application of this technology in regard to cobots achieves new goals. Cameras allow the cobot to identify its position relative to its environment. Pilz, an automation safety technology supplier based in Germany, invented the SafetyEye, “the first safe camera system for 3D zone monitoring” [18]. SafetyEye is suitable for cobots for it provides uninterrupted, live visual observations of specific danger zones. Cobots need this technology in order to take precautionary measures for human safety. SafetyEye has a sensing device that receives information from three cameras mounted from the ceiling, providing a top down view of the work area. Figure 1 displays the sensing device and control systems.
unit. These cameras can monitor up to an area of 9.8 x 7.4 meters [19]. The images retrieved from the cameras are accessible from the accompanying software.

![Figure 1](image1.png)

**Figure 1 [19]**
**Pilz’s SafetyEye set**

The user can divide the work space into smaller volumes according to one’s desired limitations on the system. In the software, the divided volumes, or zones, are 2D cross-sections from the top down view provided by the cameras extruded to a given height parameter creating the volume. These zones are differentiated as warning or safety zones, and are identified by the yellow or red volumes. If motion is sensed in the yellow zone, the worker will be notified of their increasing proximity to the cobot through the sounding of an alarm. When this happens, the control unit will force the machinery to slow down. This will encourage the worker to step back in order to not slow down the system. If motion is detected in the red zone, whatever function the cobot is executing will be halted until reset [20]. This acts as an emergency safety switch. Figure 2 displays what the selected boundaries can look like relative to the camera as a worker approaches the system.

![Figure 2](image2.png)

**Figure 2 [18]**
**A scaled view of the boundaries selected by the operator in a system monitored by Pilz’s SafetyEye**

This tool is ideal for continually evolving systems due to the ease of resetting the parameters, which can change according to different production procedures or floor plans. While, the cameras are able to sense motion they are not able to differentiate what is actually moving. Depending on the system, this may be an advantage or disadvantage. For example, a system containing multiple cobots next to each other will perform slower due to the continual movement sensed due to the nearby cobots. Similarly, systems that emit light or smoke have elicited a response from the sensing technology [20]. While keeping a worker away from flying objects or sparks would seem ideal, the worker is most likely already equipped with the appropriate gear for systems that regularly perform in such a manner.

Overall, sensory technology, like Pilz’s SafetyEye, has been widely accepted by the manufacturing world. Douglas Peterson, a general manager at Universal Robots claims that by using SafetyEye, a company will profit from this application in as little as a month [21]. SafetyEye has received recognition from the International Society of Automation and German American Chambers of Commerce, as well as the German Health and Safety Prize [19]. Adjunct safety tools, like SafetyEye, allow for existing systems to ensure superior worker safety even as the system evolves. This also allows for growth in sustainability due to worker safety being prioritized.

**Implementation in a Rear Suspension Assembly Line**

With an understanding of SafetyEye’s function, we can now analyze an application of it in an automotive assembly line. Researchers from the University of Patras created three pilot cases to help further examine the applicability of cobots. One scenario involved a cobot that is primarily used to assist a human by transporting heavy car parts. Specifically, the cobot carried and placed the wheel groups onto the left and right axle. Then, the worker checked for proper alignment and made any necessary adjustments. If correction was needed, the worker manually moved the cobot, guiding it to place the wheel groups in the appropriate spot. This manual guidance was achieved by the cobot being in a passive state, allowing the worker to manipulate the cobot without the cobot dropping or completely removing itself from the end task. After the wheel groups were properly aligned, the worker used their expertise to execute more tedious tasks, such as inserting clips and cable assembly. While the human did this, the cobot retrieved another wheel group in preparation for the next set, and the process repeated itself [22].

During this interaction, the cobot had to avoid colliding with the human given their close proximity, and especially given the worker’s exposed limbs. This system was monitored through SafetyEye. When the cobot functioned in auto mode, SafetyEye changed the cobot’s function when a worker entered the outlined area. The type and amount of change the cobot experienced depended on the confined zones selected prior to running the system. For example, when the worker entered the yellow zone, the cobot’s speed was reduced. Then, once the worker exited the monitored area, the cobot would then return to auto mode and run at full speed. SafetyEye was beneficial
in this situation due to the visible distance between the cobot and the worker. If the interaction between the cobot and the worker occurred in a tighter space, overhead cameras would not suffice. Overhead cameras are ideal for systems that do not regularly require direct contact with the cobot. The worker and cobot need to be far enough away from each other in order for the camera to be able to effectively monitor the area. In a closer interaction, additional safety features will need to be added directly onto the cobot to control the cobot’s speed and monitor its position.

The use of a cobot in this stage of the assembly process eliminates the heavy lifting that the worker would have previously done. Specifically, in this interaction, the most weight the worker lifts is a 1.5 kg screwdriver. Reducing the more labor-intensive tasks for the worker to complete will not only decrease the fatigue felt by the worker, but will speed up the system due to the assistance of the cobot.

As previously discussed, cobots can increase production rates when implemented properly into a system. This scenario highlights that cobots can be beneficial in assembly lines, not only for the productivity of the system but for the well-being of the company’s employees as well. As companies are continuing to prioritize their workers’ health and satisfaction, researchers are pursuing new components of cobots that increase a human’s comfort level when working with cobots.

**Research on Animated Faces for Cobots**

Cobot-human interaction is optimized when systems that prioritize the workers’ safety are used, which was discussed earlier. Once the worker is aware of the system’s structure, the next step is to improve the interaction between the cobot and the human to further establish a sense of safety. This can be achieved by making the cobot interact in a way that humans instinctively respond to. Humans are social beings and are proficient in reading social cues, such as eye contact. For this reason, cobots can have screens attached, like a head, to allow the worker to read the facial expressions on the screen. The screen may display different background colors along with eyes and a mouth. The facial expressions from the screen are designed to stimulate an emotional response from the worker. By affecting the emotional state of the worker, warnings can be communicated. Additionally, the eyes can move in the same direction as the cobot’s next movement, providing another form of communication between the worker and cobot.

Researchers from the University of Pennsylvania, Naomi Fitter and Katherine Kuchenbecker, designed 49 animated faces for the Baxter Research Robot utilizing seven colors (red, orange, yellow, green, blue, purple, and gray) and seven expressions (afraid, angry, disgusted, happy, neutral, sad, and surprised). The creator of Baxter, Rethink Robotics initially created a proprietary set of faces for Baxter, but these images are not available to researchers. For this reason, Fitter and Kuchenbecker decided to further study the effects of animated facial expressions on cobots in aiding communication with humans. Three factors (face color, facial expression, and onlooker country of origin) affected the onlooker’s perceived feelings towards the robot with facial expression having the largest effects. Figure 3, below, displays several of the combined background colors and facial expressions.

![Figure 3](image-url)

**Combinations of background colors and facial expressions that participants received in the survey**

The Baxter Research Robot, created by Rethink Robotics, is safe, flexible, and affordable as well as capable of completing a handful of different tasks. Baxter is trained by demonstration instead of programming, which allows for reduced time and costs. Its versatility on the assembly line is achieved by the ease of retraining the cobot, allowing it to be quickly repurposed for other jobs. The Baxter Research Robot is equipped with sensing technology to “feel” its surroundings in order to position itself appropriately. Finally, Baxter’s arms move like human arms optimizing the work space in the cell reconfiguration.

To collect data on the human response to the cobot facial expressions, two surveys were released. The first surveyed Baxter Research Robot owners on how they use their cobot and what they display on the screen. The second surveyed a user’s response to fourteen randomly selected pictures of the animated faces. The participant identified on a scale how they perceived the robot’s pleasantness, the robot’s energetics, how safe they felt while looking at the robot, and how pleased they felt while looking at the robot were presented with each face. This survey was distributed online through Amazon Mechanical Turk, and reached people in the US as well as India, specifically, 286 U.S. citizens and 282 citizens of India, with 44.2% being technically trained and 6.2% having owned robots before. By analyzing the responses from people across the globe, they were able to identify if there was a noticeable difference in the perception of robot faces depending on the onlooker’s country of origin. This investigation hoped to gain a “coarse understanding of how particular faces affect onlookers” as opposed to “rigorously exploring every aspect of robot faces.”
A similar 83.3% reported interest in an open-source database of expressive Baxter faces [23]. Of the 83.3% reporting interest, 66.6% “desired subjective data about how human raters perceive different Baxter facial expressions” [23]. The owners using Baxter for human-robot interaction were all interested in open-source expressive Baxter faces, and “75% of them also wanted human ratings” [23]. There was also interest in more facial expressions as well as background colors [23].

Through the Amazon Mechanical Turk survey, researchers concluded that robot face color slightly affected participant responses. Face color significantly affected the ratings of all four areas (robot pleasantness, robot energetics, personal safety feeling, and personal pleased feeling). A post-hoc multiple comparison test revealed that the color red made the robot seem the least pleasant but, the most energetic, the least safe, and the least pleasing. A stronger statistical significance was found in each of the four areas when analyzing the results of the survey in regard to the expression of the face. Country of origin of the survey participants was found to have a small but significant effect in all four areas. When analyzing the survey results further, it was indicated “robots designed to look pleasant will inherently make onlookers feel safer and pleased” [23]. Figure 4 depicts the resultant facial expression as well as background color in regard to robot energetic-ness and pleasantness.

Overall, the survey found that there is interest in expressive, open-source Baxter faces and that the different expressions portray different emotions and feelings to a human. Facial expressions had the largest impact on participants’ perceptions in the areas of robot pleasantness, robot energetics, personal safety feeling, and personal pleasantness feeling, but background color and country of origin did have some impact as well. The results indicated that Indian participants identified a higher feeling of safety around the cobots than the US participants. Another component to take into account is that the survey was designed by Americans, and may cater differently to people of other origins. In order to affect human-robot relationships the most, it would be most effective to use the color red [23]. Clearly, robot expression and face color are worth continuing to utilize in human-robot relations as well as improving upon in the future to create the best interactions.

In regard to the survey, it is evident that animated faces are an important safety feature for cobots. The whole idea behind cobots is to create a safer, more comfortable environment for the worker. The best way to achieve this is by strengthening human-cobot interactions. The results from this study make it clear that one of the best ways to strengthen human-cobot interaction is by giving cobots faces. These faces allow cobots to take on more human qualities, which then allows them to send necessary signals back to the human to establish a safer environment. While facial options are limited at the current time, it is clearly a feature that will be built upon in the future.

The continued development of these animated faces is also important for sustainability. As mentioned previously,
sustainability is enhanced when employees are safe. The animated faces being developed for cobots allow for a safer work environment due to their ability to create an emotional response from a worker, as stated earlier.

MORE THAN JUST MANUFACTURING: THE LASTING IMPACT

As engineers and members of society, it is our responsibility not to put anyone in harm's way. The first step is to fix existing systems, so that they meet modern safety standards and promote the longevity of the system. This can be accomplished by completely removing outdated, hazardous technologies or incorporating sustainable tools that make up for the system’s inabilities. As mentioned previously, while robot related deaths account for a very small fraction of all work-related fatalities, any accident has a large effect on companies and businesses. Accidents that occur on the job result in lost work hours, increased insurance rates, workers’ compensation premiums, and possible litigation [25]. Co-workers of the injured employee have to stop to deal with the injury, which results in a loss of productivity. Productivity continues to be lost when co-workers are distracted or have to take time off work as a result of the accident [25]. Productivity tends to be increased when workers feel that they are in a safe environment where fatal accidents do not occur [9].

With cobots, sustainability is enhanced. Sustainability, to reiterate, is seen in the form of enhanced employee, community, and product safety. It is also seen in increased operation efficiency due to reduced cost and waste [3]. As explained, cobots help reduce cost due to being flexible and easily retrainable. Another way cobots reduce cost is by decreasing human idle time and therefore increasing productivity. Reduced costs are also brought on by the decrease in robot related accidents considering cobots do not need to be kept in cages like industrial robots. The decrease in accidents also goes hand in hand with the safety aspect of sustainability.

With more efficient manufacturing systems, everyone reaps the benefits of higher quality products in a faster period of time. Companies will be able to better meet consumer demands as consumers continue to receive their desired product with consistent quality.

THE FUTURE WITH COBOTS

To reiterate, cobots are more beneficial in the workplace and on assembly lines than industrial robots. Cobots are smaller, more mobile, and more flexible than industrial robots, which are kept in cages away from workers. In contrast, cobots create a more productive environment as they can work alongside their human counterparts on the assembly line. Cobots, because of their flexibility and mobility, can be found in a variety of different fields and these areas for cobots to be utilized are continuing to increase as the technology continues to be improved upon. While cobots are currently present in more of a workplace environment, in the near future, they could be found in homes and other personalized areas [5].

Cobots contribute to creating a safer work environment because they are designed to work alongside human beings. Furthermore, with safety add-ons, like a monitoring system and improved communication, cobots optimize their interactions with humans. As cobots continue to be improved upon, workers will only gain more comfort in working alongside them. As indicated by our research, more applications for cobots will continue to be discovered as a result of the continual evolution of cobots. The possibilities for the uses of cobots have the potential to be endless due to the newness of the field.

SOURCES


ADDITIONAL SOURCES


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