

ROBOTICS IN THE WORKPLACE

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1 INTRODUCTION

In the years since the first robot was patented in 1961, robots and robotic systems have proliferated through many sectors of the economy including manufacturing, logistical support, medical technology, law enforcement, and military applications. Advances in digital technologies, as well as development of core technologies in camera systems, communication systems, sensors, and displays, are changing the capabilities and possible applications of robotics across industries. Robots have the potential to improve quality of life by performing tasks that are fatiguing, infeasible, or dangerous for humans to perform (1). As robots gain broader applications, there are concerns about potential unintended consequences such as safety, health, and fairness issues for workers. Robots present new challenges and new opportunities for occupational safety and health professionals. This chapter examines the potential hazards and risk-reduction benefits of using modern robots in the workplace.

1.1 Historical Development: Born Out of Fiction

The word “robot” comes from the Czech word “*robota*” meaning “work,” or “forced labor.” The first popular use of the word robot was in a 1920 science fiction play, “R.U.R. (Rossum’s Universal Robots),” by Karol Čapek. The play is set in a factory staffed by robots and designed to build

more robots. The robots described in R.U.R. were simulated humans, biological creations rather than mechanical devices. By the closing act of R.U.R., Čapek’s robots have revolted, taken over the world, and wiped out the human race except for the few individuals who they need at the R.U.R. factory to help create more robots (2). Starting in 1939, science fiction writer Isaac Asimov wrote a series of short stories featuring mechanical robots controlled by a “positronic brain.” In one of his short stories, *Runaround*, later incorporated into the compilation, “*I, Robot*,” Asimov introduced the three laws of robotics as a safety feature to protect humans from robot activity (3):

1. A robot may not injure a human being or, through inaction, allow a human being to come to harm.
2. A robot must obey the orders given it by human beings except where such orders would conflict with the First Law.
3. A robot must protect its own existence as long as such protection does not conflict with the First or Second Laws.

A later addition was the *Zeroth Law* of robotics, “A robot may not harm humanity, or, by inaction, allow humanity to come to harm.”

Inspired by Isaac Asimov’s science fiction, inventor George Devol patented in 1954 the first industrial robot designed “to move material from one place to another” (4). Devol called his robotic arm a *Unimate*. In 1956, Devol met entrepreneur Joseph Engelberger and formed a partnership

Mention of any company or product does not constitute endorsement by the U.S. Government.

that led to the commercialization of Devol's invention. In 1961, they formed Unimation, Inc. Their collaboration set the foundation for the future robotics industry. In 1966, Engelberger demonstrated the Unimate on the *Tonight Show* with Johnny Carson introducing the robot to the public. On the show, the robot performed several maneuvers including putting a golf ball, pouring a beer, and conducting the *Tonight Show* band (5).

By 1969, General Motors was using the Unimate robotic arm to spot weld on its production lines. Unimation, Inc. licensed Nokia to manufacture robots for Scandinavia and Europe. In 1969, Engelberger licensed Kawasaki Heavy Industries to manufacture and market the Unimate robots for the Asian market. Today an increasing number of robots from multiple manufacturers are used in the workplace. The International Federation of Robotics (IFR) estimated in 2016 that the worldwide stock of industrial robots exceeds 2.4 million robots, and is growing by 15% annually (6).

The initial wave of industrial robots, introduced in the 1970s, was introduced in the manufacturing sector and specifically for assembling automobiles. The second robotic wave took off at the turn of the twenty-first century with the introduction of service robots. It was facilitated by the increasing autonomy and sensory capabilities of robots coupled with decreasing cost and size of microprocessor controllers. With the availability of relatively inexpensive collaborative robots capable of working in direct contact with people, we are now entering the third robotic wave where robots operate alongside workers. In addition, workers are now being equipped with performance-enhancing robotic devices such as robotic exoskeletons and other capacity-enhancing prostheses.

2 CATEGORIES OF ROBOTS

The International Organization for Standardization (ISO) defines a *robot* as, “an actuated mechanism programmable in two or more axes with a degree of autonomy, moving within its environment, to perform intended tasks,” including “its control system and the interface of the control system” (7). The ISO classifies current robots as industrial robots and service robots. In addition, ISO describes collaborative robots, or “cobots,” as robots operating within a defined collaborative workspace with workers, which includes both industrial robots and service robots. This chapter elaborates on industrial robots, service robots, and collaborative robots based on the ISO classification.

2.1 Industrial Robots

The ISO defines *industrial robot* as “an automatically controlled, reprogrammable, multipurpose manipulator,

programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications” (7). Industrial robots, characterized by high strength, endurance, and precision, are widely used for welding, painting, assembling, and material moving.

According to the IFR, industrial robot sales increased by 6% to 422 271 units in 2018, with growth in the electrical/electronics industry growing by over 41%. The electrical/electronics industry is a close second, consuming 25% of the total supply in 2018, while the automotive industry segment represents the largest consumer of industrial robots accounting for 30%, metals and machinery at 10% and plastics and chemical products at 5% of the total supply.

Globally, 74% of industrial robot sales occur in just five countries: China, the Republic of Korea, Japan, the United States, and Germany. The greatest growth has occurred in China, which in 2018 purchased 36% of the world's supply of industrial robots (6). The major driver of this growth is in the electrical/electronics industry for the manufacture of computers, communication devices, medical equipment, precision, and optical instruments. Robot usage in the United States is behind that of several countries, including the leader in use of robots for production – South Korea (8).

One multinational manufacturing company that builds a range of mobile devices recently replaced half of its workers with robots (9). The company, Foxconn, has plans to expand its use of robots in electronics manufacture replacing all repetitive task jobs with robots. The company itself is morphing from a components manufacturer to one that creates and exports robots (10).

2.2 Service Robots

The ISO defines a *service robot* as one “that performs useful tasks for humans or equipment excluding industrial automation applications” (7). Professional service robots are further differentiated as a service robot used for commercial tasks, usually controlled by a trained operator, while personal service robots are used for noncommercial tasks. Like industrial robots, professional service robots manipulate and navigate their physical environments. Unlike industrial robots, service robots typically operate in unstructured and highly unpredictable environments. For example, they may operate in disaster areas independently, without an operator. Alternatively, they may operate with people present, such as in hospitals.

According to the IFR, from 1998 to 2017, about 285 000 professional service robots were placed in service, although it is not clear how many of them are still in operation. In 2018, the number of service robots increased by 61% over 2017, with over 271 000 units sold. Autonomous guided vehicles (AGVs) represented 41% of all service units sold. Another 39% of the service robots were sold for inspection and maintenance purposes. There are many additional

applications for service robots including logistic systems, defense robots, farming robots such as cow milking robots, public relations robots, powered human exoskeletons, and medical robots (11).

Logistic systems may include automated guided vehicles used in manufacturing and nonmanufacturing environments to move materials, supplies, and products. These systems account for 25 400 of the service robots installed in 2016. The 11 100 service robots in defense applications in 2016 accounted for 19% of the total. The greatest application for defense service robots was in unmanned aerial vehicles (UAVs) also referred to as “drones.” Sales of medical robots, used to assist in surgery or therapy, increased by 23% to 1600 units, accounting for 2.7% of the total unit sales of professional service robots (11).

2.3 Collaborative Robots

The ISO has defined a *collaborative robot* as “a robot designed for direct interaction with a human” (7). Depending on the application area, collaborative robots or cobots could be any of the types of robots described previously: industrial, professional, or personal service robot. For example, the ISO Technical Specification (TS) 15 066 “Robots and robotic devices – Collaborative robots” defines industrial collaborative robots as operating within a defined collaborative workspace, where the collaborative workspace is defined as a workspace within a safeguarded space where the robot and a worker can perform tasks simultaneously during production operation (12).

Collaborative robots strive to combine the dexterity, flexibility, and problem-solving skills of workers with the strength, endurance, and precision of mechanical robots. In 2007, Pils GmbH & Company launched a multi-camera computer system that monitors the area surrounding robots and adjusts their behavior accordingly. The system, called *SafetyEYE*, allows a robot to perform tasks without sectioning off the entire area from workers. Thus, this system allows robots to perform their tasks collaboratively with workers in the same workspace. A robot equipped with such a system can move around freely but can slow its movements if a worker approaches or, if the robot gets too close to the worker, stop altogether without disrupting activities of the entire workspace (13).

In 2009, Universal Robots of Denmark introduced the UR5 collaborative robot, initially available on the Danish and German markets only (14). In 2011, a first humanoid collaborative robot, R2, was launched into space to work alongside astronauts and cosmonauts on board of the International Space Station (15). By 2012, several car manufacturers deployed collaborative robots on their assembly lines. For example, in December 2012, German carmaker BMW introduced a slow-moving collaborative robot in its factory

in Spartanburg, South Carolina, which co-operates with a worker to insulate and water-seal vehicle doors (13). The robot spreads out and glues down material that is held in place by the human worker’s fingers which are more agile.

A new field of collaborative robotics is managerial robotics. Instead of being limited to mundane, repetitive, and precise job tasks, some researchers are exploring the potential for robots to serve as managers, e.g. supervising workers and assigning tasks. Robots with perfect memories, internet connectivity, and high-powered computers for data analysis can keep precise records of project progress and provide real-time scheduling and decision support. With perfect recall, they can remind their human colleagues of complex policies and procedures, all while communicating in a natural, social way (16). Researchers have shown that correlations between autonomy and sociality for collaborative robots could lead to robots succeeding in management roles (17).

3 ROBOT RISK ANALYSIS

Robot technologies provide the potential to remove and isolate workers from hazardous work environments where health-related risk exposures and machine-related injuries continue to occur. However, robots may introduce new risks or exacerbate existing risks that could lead to worker injuries or fatalities.

In the traditional caged robot incidents, “human in danger work zone” and “sudden robot movement” are the two primary sources for safety problems (18). A serious injury incident can occur when both risk factors are present as indicated in the fault tree diagram (Figure 1). The *fault tree analysis method* is a tool that uses Boolean logic to combine probabilities for independent and sequential events. For instance, a worker may unintentionally enter a robot cage with no injury incident. Alternatively, a robot’s power may be engaged putting it in operation unexpectedly and cause no injury. However, the worker is at increased risk if both conditions are met, i.e. the worker is in the robot cage when the robot’s power is engaged, and an operation is started unexpectedly. By controlling the influential sub-factors of the two primary factors, adverse robot incidents can be avoided by breaking the chain of injury initiation.

A fishbone diagram is also a tool that can help perform a cause-and-effect analysis, i.e., to discover the root cause of a potential robotic problem. In the diagram, the “fish head” represents the problem to be solved – i.e. a worker injury involving a robot. The three major cause categories of robot incidents are human and task factors, robot system factors, and environmental factors (Figure 2). The deeper causes are intentional entry, unpredicted human movement, unauthorized entry, robot system error, and electromagnetic interference. By focusing prevention efforts on the root causes of

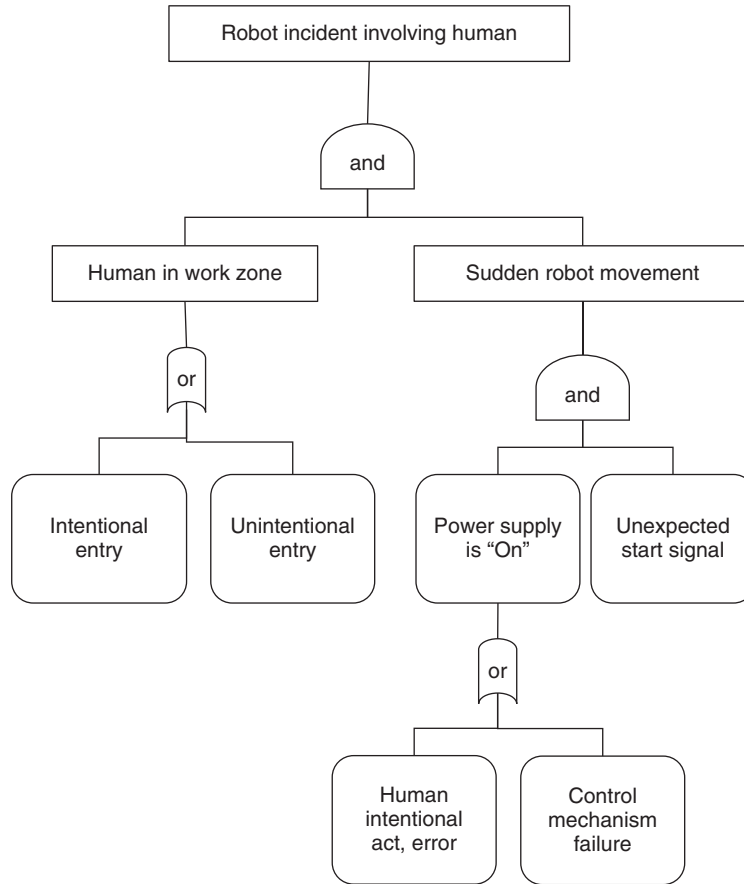


FIGURE 1 Fault tree diagram for industrial robots.

these factors, the occurrence of similar robot incidents can be prevented.

3.1 Industrial Robots – Risk Analysis

Industrial robots can pose several types of hazards:

1. mechanical hazards such as those arising from unintended or unexpected movements or release of tools;
2. electrical hazards such as contacts with live parts or connections or exposure to arc flash;
3. thermal hazards such as those associated with hot surfaces or exposure to extreme temperatures;
4. noise hazards; and
5. other hazards such as vibration, radiation, and chemicals (19).

There are two main categories of worker injuries from working around industrial robots – those due to random hardware failures and systematic failures that are mistakes or oversights in the design or user errors. Hardware failures

include the robot’s mechanics (e.g. loose connections across parts, faulty electronics), unintended movement or actions from the controller because of systematic software design errors (e.g. programming bugs, faulty algorithm). Consequently, a robot’s arm might fail to stop because of a contact sensor malfunction, or a robot arm might achieve high, uncontrolled speed, abrupt motion, or acceleration due to an engineering failure (20). Human sources of injuries such as errors in programming, interfacing peripheral equipment, connecting input/output sensors, can all result in unpredicted movement or action by the robot that can result in personnel injury or equipment breakage. The greatest human judgment error results from becoming so familiar with the robot’s redundant motions that personnel are too trusting in assuming the constancy of these motions and place themselves in hazardous positions while programming or performing maintenance within the robot’s work zone (21).

There are few reports detailing incidents involving robots. The National Institute for Occupational Safety and Health (NIOSH) conducted one detailed fatality investigation, describing a case where a worker was performing maintenance on an industrial robot. On 21 July 1984, a 34-year-old

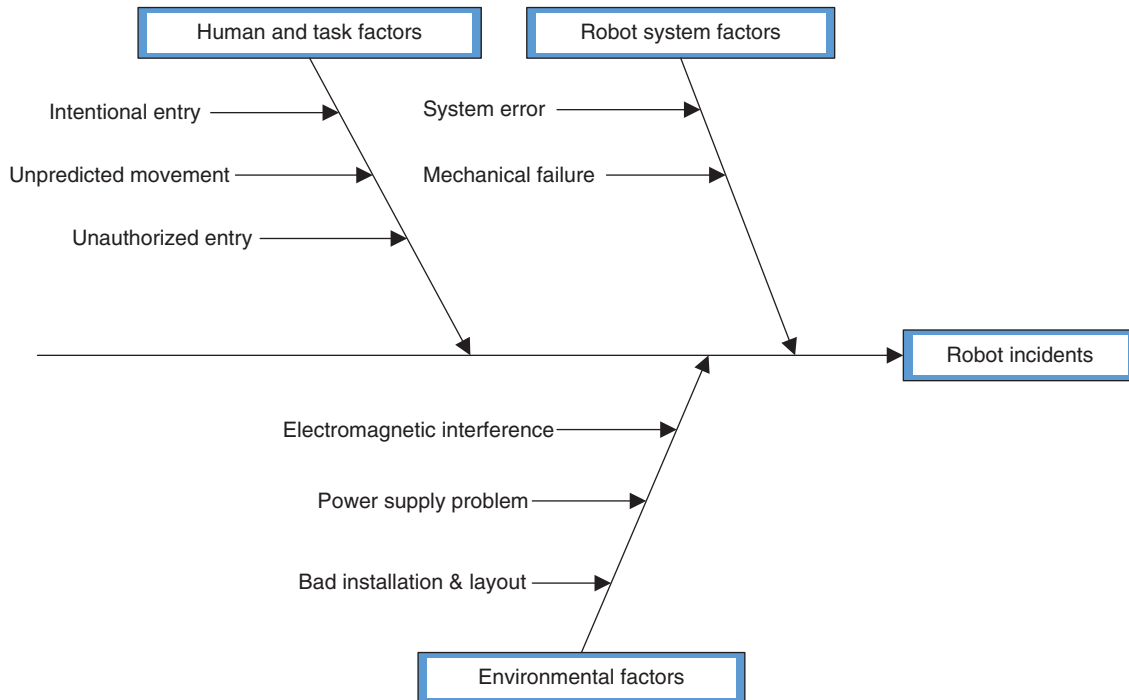


FIGURE 2 Fishbone diagram – root cause analysis.

die cast operator with 15-years of experience went into cardiopulmonary arrest after being pinned between the right rear end of a hydraulic robot and a safety pole. A fellow employee saw the victim pinned between the right rear of the robot and a safety pole in a slumped but upright position (Figure 3). The subsequent investigation found that: (i) operators should never be in the work envelope while the robot is operational; or (ii) if programming must be done inside the work envelope while the robot is operational, programmers should operate the robot at a slow speed and be made aware of all the possible pinch points where the body or extremities could be trapped (22). In a 1987 report, 32 reported cases of robot incidents were analyzed (23). Reported findings indicate that line workers (23 cases) are at greatest risk, followed by maintenance workers (6 cases) and programmers (3 cases). Pinch-point injuries accounted for 56% of all injury events, while impact injuries accounted for 44%. Most injuries were caused by poor workplace design (20 of 32 injury events) and human error (13 of 32 injury events) and not sensor or engineering failures.

Most recently, a German newspaper reported that a worker, an employee of a third-party contractor, was killed while installing an industrial robot at a Volkswagen assembly line on 30 June 2015 in Baunatal, Germany. The robot gripped and pressed him up against a metal plate, crushing his chest. Despite efforts to revive him, the worker later died at a hospital. It is unclear whether this fatality was caused by robot system failure or human error. This

case and others of workplace incidents involving industrial robots suggest that additional safety measures for worker interactions with industrial robots are necessary (24).

3.2 Service Robots – Risk Analysis

Physical proximity between professional service robots and workers are much more common than between industrial robots and workers since they often share the same workspace. Therefore, worker isolation from the professional service robot is no longer an option as the main safety approach. Service robots operate in a more complex environment with a higher degree of autonomy and mobility. This autonomous and mobile behavior can result in dangerous situations for workers. For example, people seem to perceive autonomous robots, especially those with “humanoid” features, differently than they do with most other computer technologies. People tend to “over-attribute” to these robots human-like qualities and capabilities than they actually have (25) and commonly give them human-type names (26).

In addition to engineering and human sources of injuries, adverse environmental factors such as extreme temperature, poor sensing in difficult weather or lightning conditions can lead to incorrect response by service robots and can be a source of injury. There are several standards in development to deal with safety for service robots with collaborative functions (27).

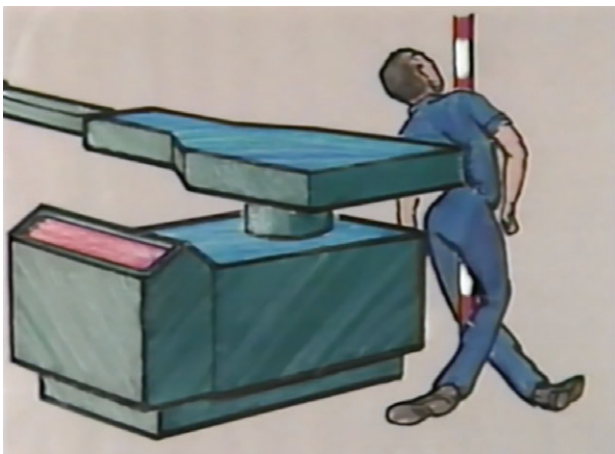
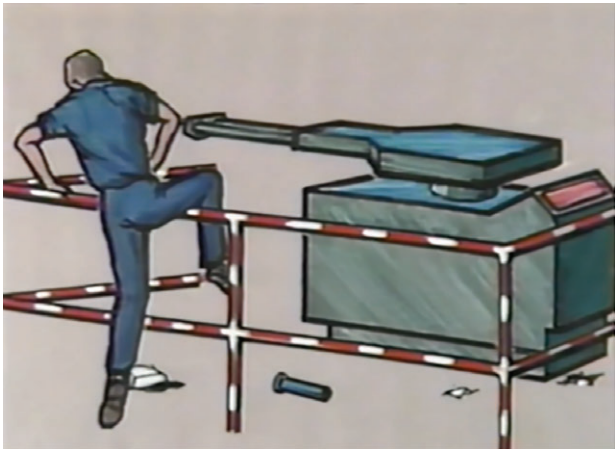


FIGURE 3 Worker enters exclusion area while robot is energized and is crushed in pinch-point. Source: Modified from www.cdc.gov/niosh/face/in-house/full8420.html.

3.3 Collaborative Robots – Risk Analysis

Collaborative robots are defined as, “a robot designed for direct interaction with a human” (7) that can be any of the types of robots described previously, industrial, professional, or personal service robot. Collaborative robots combine the dexterity, flexibility, and problem-solving skills of human workers with the strength, endurance, and precision of a mechanical robot.

The on-going introduction of advanced industrial, professional service, and collaborative robots working alongside of workers requires occupational safety and health professionals to take a proactive approach to the assessment and management of the risk profile of occupational robotics. To ensure that workers are protected, the following measures for occupational robotics have been recommended: (i) occupational safety and health professionals should be directly involved in the development of

international standards (ISs) aimed at ensuring safety of workplaces with humans and robots; (ii) workplace safety standards for maintenance, operation, and interaction with workers, of professional, personal service, and collaborative (including managerial) robots should be developed; (iii) proactive approaches for establishing risk profiles of robotic workplaces should be developed; and (iv) redundant safety measures should be developed and operationalized to protect workers while performing maintenance tasks on robots (28). These measures, and others suggested by experts, could be incorporated into industry standards before potentially unsafe robots enter the twenty-first century workplace.

4 RISK MANAGEMENT

4.1 Industrial Robots – Risk Management

The main approach to industrial robot safety, especially for the high-power robots, is maintenance of a safe distance between workers and operating robots through the creation of “guarded areas.” Worker entrance into the safeguarded area would require a shutdown of the robot. Shutdown of one robot for safety reasons in an assembly line of robots can impair productivity and may be a disincentive to achieving the highest level of safety for the worker.

Detailed safety recommendations regarding the design of industrial robotic systems, the training of workers, and their supervision can be found in two publications from NIOSH: “Preventing the Injury of Workers by Robots” (29), and Safe Maintenance Guidelines for Robotic Workstations (30). Although somewhat dated, the alert and the safety guidelines are still valid for industrial robots fixed in place. For the design of industrial robotic systems, NIOSH recommended that robotic systems include:

1. Physical barriers that incorporate gates with electrical interlocks and backup sensors stopping robots when the gate is open.
2. Barriers between robotic equipment and any free-standing objects to eliminate pinch points.
3. Adequate clearance distances around all moving components of the robot.
4. Remote diagnostic equipment.
5. Adequate illumination around the robot working area.
6. Placement of clearly visible marks on working surfaces or floors that indicate the zones of maximum robot movement.

In addition, safety training and refresher courses specific to the particular robot in question should be provided to workers who will be programming, operating, or maintaining robots. Supervisors should ensure that workers do not enter

the operational area of a robot without first putting the robot on “hold,” in a “power down” condition, or at a reduced operating speed mode, and ensure that workers doing automated tasks are closely supervised (e.g. video monitored).

There are several reasons why workers enter robot-operating areas such as to set up a job, to re-program the robot, to inspect the robot operational system, or for routine maintenance. The injuries that have occurred to workers have happened most frequently during corrective maintenance. The technical report (TR), “Safe Maintenance Guidelines for Robotic Workstations,” describes approaches for preventing unexpected or unintended robot motion which can cause injury to workers whose job is to correct abnormal functioning of industrial robotic systems (30).

4.2 Consensus Standards – Industrial Robots

The American National Standards Institute (ANSI) and the U.S.-based Robotics Industry Association (RIA) published the first robotic safety standard for industrial robots in 1986 as ANSI/RIA R15.06 “American National Standard for Industrial Robots and Robot Systems – Safety requirements.” Major ISs for robots were developed by the ISO Technical Committee (TC) 184 (Automation systems and integration) Sub-Committee (SC) 2 on Robots and robotic devices. Effective 1 January 2016 ISO TC184/SC2 became a new ISO TC: TC299 Robotics, whose scope is “Standardization in the field of robotics, excluding toys and military applications” (31).

TC 184, SC 2, has published a standard in two parts dealing with the general safety of industrial robots:

1. ISO 10218-1:2011, Safety requirements for industrial robots – Part 1: Robots; and
2. ISO 10218-2:2011, Safety requirements for industrial robots – Part 2: Robot systems and integration (19).

These standards originate from a standard developed by the U.S.-based RIA and published in 1999 by ANSI as ANSI/ RIA R15.06 Safety of Robots, Integration of Robots, Robot Systems, Robot Cells. The ANSI/RIA R15.06 was updated in 2012 (approved in 2013) as “Industrial Robots and Robot Systems – Safety Requirements” to include robot collaboration (see discussion in **Ethics in Industrial Hygiene**). The newly established TC299 is in the process of updating the ISO 10218 and is developing industrial robot safety standards for specific elements of robotic systems. The committee published TR 20218-2 “Robotics – Safety design for industrial robot systems – Part 2: Manual load/unload stations” in 2017 and TR 20218-1 “Robotics – Safety design for industrial robot systems – Part 1: End-effectors” in 2018.

4.3 Service Robots – Risk Management

Professional service robots such as remote-controlled robots commonly have unidirectional interaction with their human operators. In this mode of interaction, the operator controls the robot, which sends back information about its environment and its task (32). For such professional service robots, their interaction with workers is limited, and inactivation of a robot for servicing can be used to minimize risks during maintenance. Most of the professional and personal service robots operating autonomously are equipped with collision detection and avoidance systems (33), which reduce the possibility of a harmful physical contact during unplanned encounters with workers. Other approaches to minimizing risks of service robots are reducing their weight, size, and operating speeds and forces. However, these approaches cannot eliminate collisions and other methods for improving safety are necessary (34). In addition to engineering and human sources of injuries, adverse environmental factors such as extreme temperature, poor sensing in difficult weather or lightning conditions can lead to incorrect response by service robots and can be a source of injury (20). Yet, despite the proliferation of safety concerns involving service robots in the same workplace as workers, ISs have not yet been developed to address worker safety in maintaining or operating professional and personal service robots.

4.4 Collaborative Robots – Risk Management

Since collaborative robots function alongside workers, isolation as a safety measure is not an available control option. Other safety approaches must be developed and implemented, for example proximity sensors, appropriate materials, software tools, and similar controls (20). Workspace sharing without any resultant harm to workers or the robot has been the goal of research in the domain of physical and cognitive human–robot interactions. The research on physical safety of humans and robots in the collaborative space falls into three categories (35):

1. interaction safety assessment and the quantitative description of the human-robot safety concept (36);
2. interaction safety through design, such as lightweight manipulators, passive compliant systems, safe actuators, and passive robotic systems; and
3. interaction safety through planning and control such as navigation and collision avoidance in an environment shared by human and robot through proactive safety systems and control of the stiffness/pliability to reduce the impact force during collisions (37).

Collaborative robots interact multidirectionally with their human collaborators. In this new mode of interaction, the

information exchange between workers and robots flows in multiple directions and is on an equal level of importance with regard to work processes for both workers – human and robot.

In this new era of workplace, the design of robots should ensure that the motions of the robot are predictable to humans and do not cause any unpleasant emotional reactions like fear, shock, or surprise. The ability to read human emotions is a capability that would not only improve the functionality of collaborative robots but also improve their safety profile. Several methods are being investigated such as behavior pattern recognition, on-skin sensors, or other similar methods that would enhance the ability of a robot to “read” human emotion (38).

Another example of novel approaches to improve the emotional safety profile of collaborative robots is the ability of certain models “to act like a human worker.” For example, the robot could have an “eye” looking in the direction of the worker and be able to react to the human’s facial expressions indicating danger, distress, or fear. Though such capabilities also bring new safety issues with them, e.g. workers might unintentionally attribute nonexistent “reasoning” or “recognition” capabilities to robots (39). These enhanced capabilities are being developed in collaborative “humanoid” robots. Humanoid robots, by virtue of their appearance and behavior, appeal to people differently than other robots (40). A 2004 study of cognitive interactions suggests that humanoid robots may be appropriate for settings in which people have to delegate responsibility to robots or when the task is too demanding for a human to do (41).

As workplace risks need to be addressed proactively (42), international safety standards for collaborative operation for robots are being developed in parallel with their rapid introduction into the workplace. Specifically, while the published ISO 10218 provides some specific guidelines for collaborative robots, ISO TC 299 more recently developed the 15066 standards on collaborative operation as a TS, which is a semi-mandatory requirement in an IS. This TC is presently working on TRs. TRs are state-of-the-science reviews and do not constitute standard requirements. This reflects the nascent nature of collaborative robots in the workplace, since more application knowledge is needed before publishing mandatory standards at the IS level. One of the issues being standardized in the TS 15066 includes guidance on the maximum force with which a robot may strike a human (“power and force limiting”). It also includes guidance on “speed and separation monitoring,” which allows for correlation in real-time of increasing danger in robot actions with decreasing distance between people and the robot (43). The latter issue was not covered in another standard developed by ISO, TC 184 SC 2 and published in 2014, ISO 13482:2014 “Robots and robotic devices – Safety requirements for personal care robots.”

Personal care robots are examples of collaborative robots as they are designed for human–robot proximity and/or physical contact. The ISO standard distinguishes three types of personal care robots: mobile servant robot, physical assistant robot (exoskeleton robots), and person carrier robot. These robots typically perform tasks to improve the quality of life of intended users, regardless of age or capability. The ISO standard describes hazards associated with the use of each of these three robot types and provides requirements to eliminate, or reduce, the risks associated with these hazards to an acceptable level. Thus, ISO 13482:2014 does not include workplace safety considerations for personal care robots used in home settings, such as their maintenance or interaction of personal care robots with home healthcare workers.

ISO/TS 15066:2016 specifies safety requirements for collaborative industrial robot systems and the work environment and supplements the requirements and guidance on collaborative industrial robot operation given in ISO 10218-1 and ISO 10218-2. ISO/TS 15066:2016 applies to industrial robot systems as described in ISO 10218-1 and ISO 10218-2. It does not apply to nonindustrial robots, although the safety principles presented can be useful to other areas of robotics. Safety certification requirements for domestic robots have been described (44).

5 ROBOTIC APPLICATIONS FOR RISK REDUCTION

5.1 Exoskeletons and Physical Assistant Robots

There is an emerging use of exoskeleton robotic devices to increase the strength and endurance of workers (45, 46). Exoskeletons and physical assistant robots are an emerging engineering approach that claim to address the mismatch between workplace physical demands and human strength/endurance capabilities. These technologies augment the human worker’s physiologic capabilities (force and power production) in task performance. Physical assistant robots are wearable robotic exoskeletons that are fastened to the human user, or restraint-free devices that are hand-held to control the physical assistance (ISO 13482:2014). They may enable increased work capacity, or reduce biomechanical loads and/or worker fatigue, thus mitigating overexertion risk. However, while these devices may augment certain human capabilities their use introduces several potential new hazards. ISO 13482:2014 (Robots and robotic devices – Safety requirements for personal care robots) contains an informative annex listing potential hazards and consequences applicable to physical assistant robots. Some of these hazards are unique to the fastening and direct contact of the robot to the user while other hazards

are generally similar to those of robots operating in the environment. The ISO standard emphasizes the need for risk assessment and hazard identification analysis for safe operation of these robotic technologies.

A new standards development activity launched in 2017 is addressing Exoskeletons and Exosuits (ASTM F48). The scope of the F48 committee will include wearable robots. While the scopes of F48 subcommittees are in development, subcommittee F48.02 (Human Factors and Ergonomics) is expected to address workplace safety issues. Additional information about the interaction of exoskeletons and humans can be found in **Occupational Ergonomics: Past, Present, and Future**.

5.2 Unmanned Aerial Devices (Drones)

Applications of UAVs have expanded significantly in recent years. The Federal Aviation Administration (FAA) Aerospace Forecast continued growth in use of commercial UAVs with over 385 000 aircraft registered by the end of 2019 (47). The Association for Unmanned Vehicle Systems International (AUVSI) expects 100 000 jobs to be created by 2025 from the expanding market for small UAVs (48).

UAVs can be categorized into four main types depending on their primary use, e.g. military, recreational, public, and commercial. Military uses of large UAVs have a long history as surveillance tools and as weapon systems (49). Recently, public sector government agencies are finding multiple uses for small UAVs from border security to police surveillance (50). The commercial use of small UAVs is being seen across several industrial sectors such as construction, agriculture, and mining. These are the top industries that are likely to be transformed by UAVs (51).

As with other robot types, introduction of UAVs into the workplace can reduce adverse health effects in the workplace and can expose workers to a new set of hazards. A 2015 literature review summarized potential application and utility of UAVs in the discipline of occupational hygiene (52). Environmental sensing and monitoring of chemicals, aerosols, biologics, and radiation was identified as of particular importance and best suited for occupational hygiene tasks or scenarios. Additional occupational hygiene applications included UAV's employment in emergency response, safety, and industrial process optimization.

One specific commercial use of UAVs has the potential to significantly reduce incidents of injury and death is the construction industry where nearly 1000 workers died in 2015 (53). Advancements in UAV technology could help reduce construction-related injury and death from falls, toxic chemical exposures, electrical hazards, or traumatic injury from vehicle and equipment collisions. The emerging uses of UAVs in the construction industry range from aiding with construction project planning by aerial mapping of the

construction site (48), additive construction (54), and the actual building of structures (55).

Another commercial use of UAVs is for the surface mining industry. UAVs could reduce hazard exposure to mine workers conducting examinations and inspections around powered haulage and the working areas of the surface mine where falls of ground, rock, and material could occur. At the West Angelas Mine at the Pilbara Region of Western Australia, UAVs are being trialed to inspect stockpiles and to assist with environmental, reclamation, and maintenance activities. Other applications include traffic management of haul trucks; assessment of haul road, surface, and slope conditions; site surveys and terrain change assessments; blast planning; mine rescue, and monitoring efforts. UAVs are being used in underground mining operations to monitor ground conditions, survey, and inspect stopes (inaccessible working areas), and conduct various inspections to ensure the safety of miners (56). Operating UAVs underground poses several challenges that include the confined spaces of a mine, the lack of GPS, and no natural light.

Often, UAVs can inspect a large worksite more efficiently through aerial photography than on-the-ground personnel can. UAV detection of hazardous conditions, materials, and dangerous structures can aid in construction site hazard identification without placing a worker at risk (57). Real-time UAV systems performing remote site inspections and violation detection at construction sites may be more efficient, safer, and less costly than present construction site inspection methods (58). UAV inspection of awkward locations on and under bridges and along highways not only can reduce the cost of personnel inspecting the entire expanse of a highway road or structure but also reduce the risk of working along a busy highway or erecting equipment close to the flow of traffic. Government inspections of construction sites could also be performed by a UAV. Because drone inspection of the site would be quicker than an individual government inspector walking an extensive construction site, UAVs could increase the scope and frequency of inspections of construction projects by federal, state, and local government agencies (59). Once potential problems were identified by aerial imaging, then inspectors could focus their investigations on sites where the potential issues were imaged.

While there are many benefits to using UAVs in construction, the potential risks must be carefully studied. The presence of a UAV flying near a worker can create new hazards at a construction site, although data supporting the hazard potential of UAVs for workers are scarce. Safety professionals need to be aware of these new hazards, assess the risks arising from them, and apply controls to reduce the risks. There has been little published about the safety and health risks associated with the public or commercial use of UAVs. About 30 incidents of near-misses or crashes leading to human injury have been reported associated with the

use of recreational UAVs (60). Unstable flying conditions, operator errors, and faulty equipment may represent potential hazards to nearby workers from the commercial use of UAVs. Adding to the uncertainty about the hazards to workers from the emerging use of UAVs in construction and other industries, the arrival of autonomous or semi-autonomous UAVs may introduce new hazards arising from the absence of human control.

It is important to develop hazard identification, risk characterization, and mitigation approaches to ensure the safe operation of commercial UAVs as the use of UAVs promises significant benefits for industry. These approaches might incorporate prevention-through-design concepts such as lightweight manipulators, passive compliant systems, safe actuators, and passive robotic systems. Navigation and collision avoidance systems can be included in the design of commercial UAVs as a proactive safety measure. Collision avoidance in the three-dimensional environment is a main area of UAV design research (61). Structural designs should consider stiffness and pliability factors that can reduce the impact force during collisions.

Adequate training of operators is essential to ensure the safe operation of the UAV. A competent UAV operator is a person capable of identifying any potential hazard of operating a UAV in the construction site surroundings, especially any UAV operating condition that poses a hazard to workers on the ground. The competent UAV operator should be authorized by the construction manager to take prompt corrective measures to eliminate any hazard associated with operation of the UAV.

5.3 Rescue Robots

There are four primary categories of rescue robots: unmanned ground vehicles (UGVs) that operate on the ground surface, unmanned surface vehicles (USVs) that float on water, unmanned underwater vehicles (UUVs) that operate in water; and UAVs that operate off the ground surface (62). Rescue robots differ from traditional robots in that they must be designed to (i) operate in extreme terrains and harsh operating conditions that affect the robot size, sensor performance, and survivability; (ii) have the ability to function in environments that do not have access to GPS or wireless communications; and (iii) enable high levels of human-robot interaction with those operating the robot and survivors who are to be rescued (63). Rescue robots have been deployed for a wide variety of situations. Murphy (63) documents 34 robot deployments between 2001 and 2013 for disasters that include the 2001 World Trade Center attack, Hurricane Katrina, the 2010 Haiti earthquake, Deepwater Horizon oil spill, and the 2011 Japanese earthquake and tsunami. Most recently, several UAVs were deployed to the Leilani Estates Eruption event in Hawaii from 14 to 19

May 2018 to record SO₂ emissions, and map fissures thus reducing the risks and costs of manned helicopter flights. These deployments were conducted by a volunteer team from the Center for Robot-Assisted Search and Rescue whose mission is "... to foster unmanned systems being effectively used by formal emergency management agencies through voluntary national and international activities ..." (64).

Rescue robots often face similar challenges that include traversing rough and unstructured environments that may include debris, unstable structural components including floors, walls, and ceilings, and limited spaces and openings. Mine rescue robots are faced with additional challenges that include the need to traverse very long distances; some mines can be miles long. They also need to operate in explosive environments of methane gas and combustible dust. They may need to navigate through opaque atmospheres containing smoke and dust, through atmospheres containing toxic gases, and navigate through water in case of inundation (65-67).

Although a trend of increasing mine worker safety over time is evident, mining disasters such as the January 2006 Sago mine disaster can occur that trap miners underground. Sometimes the situations are such that self-escape is a viable option, other times miners are unable to exit the mine and so they take refuge and wait for mine rescue teams to save them. Even though these mine rescue teams are highly trained, they can encounter unforeseen events that can result in fatalities and injuries while trying to rescue trapped miners. For instance, during the 2007 Crandall Canyon coal mine disaster, two rescue workers and an inspector from the federal Mine Safety and Health Administration (MSHA) died, and six others were injured when a seismic event caused tunnel walls to collapse. Mine rescue robots are being developed to improve the quantity, quality, and timeliness of information made available to emergency responders while reducing the rescue team's exposure to numerous hazards (66). Ideally, mine rescue robotics would include the UGV, USV, UUV, and UAV rescue robot categories (63). Since mines may be flooded with water or have standing water areas and debris that can block ground access, a UAV may be the only type of rescue robot capable of travel throughout the mine (66).

Two recent research efforts into mining rescue robots include the Snake Mine Rescue Robot and Gemini Scout Robot, prototypes developed under NIOSH contracts that require further refinement before being deployed in actual rescue situations. The Snake robot (Figure 4), developed by Sarcos, is capable of being deployed thru a mine borehole that is drilled from the mine surface to the area of the mine where the trapped miners are believed to be located. A borehole can provide limited information using camera systems and sensors that can be manually lowered down the borehole to assess the physical conditions and monitor the mine atmosphere for methane, oxygen, and carbon monoxide



FIGURE 4 Snake robot lowered through borehole, then traversing a mine floor with coal and rock debris.

at that point in the mine. The data gathered are critical for mine rescue teams to determine where to deploy mine rescue teams and to determine the safety hazards they are likely to encounter. A modified pipeline inspection robot was deployed down a borehole following the Crandall Canyon Mine collapse in 2007 with some success (68), establishing the potential for a robot specifically designed for this application. The snake robot can use these boreholes to better assess and monitor conditions because it can be deployed down the borehole, up to 2000 feet deep, then using its mobility it can travel on the floor of the mine away from the bottom of the borehole. It could navigate the mine to locate trapped miners and gather situational data that would not otherwise be available. The design requirements for the snake robot include (i) fit inside a 4-in diameter borehole; (ii) operate tethered with cabling of sufficient strength to be lowered vertically 2000 ft. through a borehole; (iii) the ability to move once deployed in

the mine at one to two miles per hour; (iv) maintain mobility through a debris field, including mud and standing water; (v) measure oxygen, methane, carbon monoxide, and temperature; (vi) enable two-way voice communication; (vii) provide 200-ft minimum lateral illumination with color and infrared video; and (viii) receive power through onboard batteries and the tether cable (69).

Next, the Gemini-Scout Mine Rescue vehicle (Figure 5), developed by Sandia National Laboratories, is a UGV robot whose deployment precedes the mine rescue team to gather vital data on the mine hazards and conditions. These data are critical for the mine rescue team to plan and safely advance through the mine to reach trapped miners. The Gemini Scout design was based on a military UGV robot. The design specifications include (i) the ability to move at four to five miles per hour; (ii) transverse a debris field that includes mud and standing water; (iii) operate in wireless environment

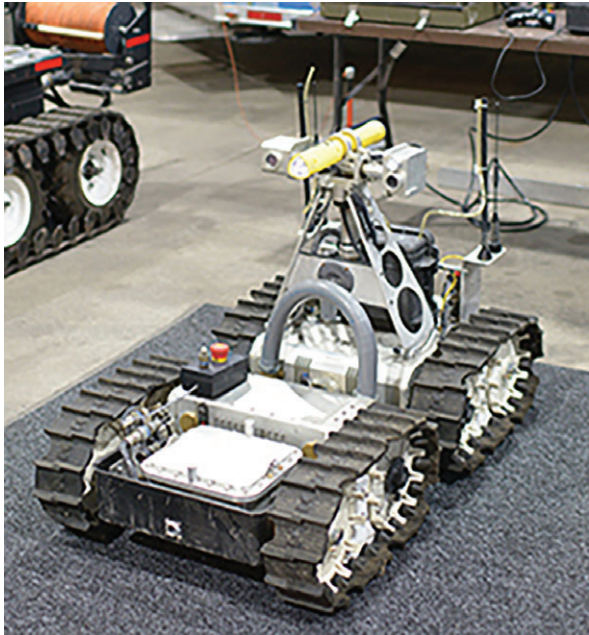


FIGURE 5 Gemini Scout mine rescue robot.

using line-of-sight technology or tethered using fiber optic cabling; (iv) measure oxygen, methane, carbon monoxide, and temperature; (v) enable two-way voice communication; (vi) provide video via on-board cameras such as color and infrared tower cameras with pan/tilt capabilities; and (vii) use front and rear navigation chassis cameras (70). The major limitation of both the Snake and the Gemini Scout is that they are not designed to operate in an explosive atmosphere that might exist in a mine emergency situation (71); incorporating explosion-proof components increases complexity, weight, and size, impacting operational mobility. Further development of these prototypes such that they are hardened and available for use in an actual emergency is planned.

The Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) was an early adopter of robotics for mine rescue. Back in the late 1990s, they developed the Numbat UGV type of robot following the 1986 Moura mine explosion that killed 12 miners. The Numbat was designed to precede deployment of a mine rescue team in order to gather mine data and conditions to enable effective safety and rescue planning while minimizing risk to personnel. The Numbat is a tethered, eight-wheeled vehicle that is controlled from a control center located at the surface of a mine. It has an ensemble of sensors to measure concentrations of methane, oxygen, carbon monoxide, carbon dioxide; video is provided by four video cameras (72). In addition, two-way communications exist via an optical fiber link between the surface and the Numbat. While the Numbat has never been operationally deployed in a mine rescue (67),

the platform has been used to further develop teleoperation and mine mapping in hazardous conditions.

The United States Mine Safety and Health Administration (MSHA) has adapted a Remotec Andros Wolverine robot originally developed for military applications for mine rescue. The robot design was modified to meet explosion-proof requirements, increasing its weight by 50% over the commercially-available model, and is referred to as the V-2. Similar to the Numbat, the V-2 is tethered and operated from a safe location, exploring up to 3500 ft. in advance of the mine rescue team (71). The V-2 has been deployed for both mine rescue and mine recovery after a fire or explosion (68); these deployments have highlighted the difficulties and limitations in operating in a post-disaster underground mine environment as well as the potential benefits robotics can provide. The manipulator arm on the V-2 has been used during mine recovery to remove debris and open doors.

6 SUMMARY

Robots are rapidly being integrated into multiple sectors of the economy from manufacturing to service industries. Despite the remarkable progress achieved by the deployment of robotics in the workplace, a fully automated robotic factory may not be on the immediate horizon. However, collaborative robots are already working beside and with human workers to carry out repetitive and precision tasks for which they are particularly well suited.

The application of robotics holds great potential for being able to reduce or eliminate human exposures in situations that would otherwise require the human to take on additional risk. For example, the recent use of robots to deal with the SARS-CoV-2 pandemic and the coronavirus disease it causes, COVID-19, is a clear example of how robots can be used for diverse tasks such as remote disinfection using germicidal irradiation with UV-C or chemical disinfectants, as well as for replacing working in close quarters with telemedicine for patient care (73). Likewise, robots have been used to access and inspect areas of the damaged Fukushima Daiichi Nuclear Power Station that would have been fatal for human technicians (74).

With humans working near autonomous robotic systems, it is critical that occupational health and safety practitioners be familiar with and engage with robotics designers and programmers to assure that workers can work safely with their robots. The use of robotics and autonomous systems is clearly going to be an important component in the future of work (75). The smooth introduction of autonomous robotic technology depends on early positive experiences of working safely with robots to build confidence. Pre-deployment consideration of occupational safety with prevention through design principles can help to assure the

development of trustworthy technology and robotic systems that ensure safety where humans and robots interact.

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