Manufacturing with mobile robotic aids: standards review and guidelines

BAHAR AHMADI[1], DAVID ST-ONGE[1]

[1] École de Technologie Supérieure
1100 R. Notre Dame O, Montréal, QC H3C 1K3
Ahmadi.bahar66@gmail.com
David.st-onge@etsmtl.ca

Abstract – This paper aims to discuss the safety standards and guidelines for mobile robots in manufacturing. With the increasing use of mobile robots in the industrial applications, it is vital to provide a set of safety measures to ensure the safe operation of these robots and protect human and the surrounding environment. In this paper, a review regarding the safe use of a mobile robot in an industrial setting and the current state of safety standards in the field will be covered. We will also concentrate on the industry's needs and handle the relevant obstacles to the development and implementation of safe applications.

***Keywords* – Mobile robots, Safety standards and measures, Industrial settings**

1 INTRODUCTION

Mobile robots have revolutionized industries such as manufacturing, healthcare, and transportation with their ability to enhance productivity, efficiency, and. However, as the use of mobile robots continues to grow, so does the need for safety standards and guidelines to ensure their safe operation and interaction with humans. Mobile robots are unique in their ability to move freely and autonomously, presenting new safety challenges that traditional robots do not face. As they navigate through unpredictable environments, mobile robots risk collisions and accidents that can cause harm to humans and damage to equipment. Therefore, it is crucial to develop safety strategies that address these challenges and ensure the safe deployment of mobile robots in various settings.

In industrial settings, the use of autonomous mobile robots (AMR) has become increasingly common for manipulative and logistical activities. With dynamic client-specific adjustments, infinite workspace, situation-aware movement planning, and better collaborative operation, AMRs offer versatility that traditional stationary robots cannot match. They are therefore vital for cutting-edge industrial applications. However, employing mobile robotics for industrial purposes necessitates stricter safety regulations and a well-organized coexistence between moving machines and human. While collaborative robots (cobots) have also gained popularity in recent years, they are different from mobile robots as they are stationary robotic arms that work alongside humans to complete tasks. Therefore, this work will focus solely on the safety of mobile robots in industrial settings, where they are increasingly used for a variety of functions such as assembly, internal logistics, and inspection.

In this paper, we review the current state of safety standards and regulations for mobile robots in manufacturing and propose benchmark and test procedures to verify the safety of mobile robots in various operating conditions. By doing so, we aim to provide a comprehensive guide for manufacturers and operators to ensure the safe and reliable use of mobile robots in industrial settings.

The rest of this paper is organized as follows. The safety components of mobile robots are described in Section 2, the safety standards for mobile robots are presented in Section 3, safety measures for mobile robots in industrial environments are discussed in Section 4.. Benchmarks and test procedure for the safety of mobile robot are provided in Section 5, andfuture trends in mobile robot safety are explored in Section 6. We hope that this review will contribute to the ongoing efforts to enhance the safety of mobile robots and pave the way for their continued use in industrial applications.

2 SAFETY COMPONENTS OF INDUSTRIAL MOBILE ROBOT

A robot system comprises a multitude of modular components that collectively provide a high degree of adaptability and versatility for various applications. The human-machine interface, task allocation and scheduling, sensors, sensor fusion and perception, motion planning, actuators, and robot control are a few examples of these. The most safety-relevant components present in every mobile robot system include sensors, robot control, robust navigation and sensor fusion.

2.1 Sensors

In the case of sensors that are mounted on a robot, safety instrumented systems (SIS) must be separated from non-critical information sources to ensure the reliability and safety of SIS. Otherwise, there is a risk that the SIS may be overwhelmed with information or become confused by conflicting information which can leads to errors in SIS.

In order to ensure safe operation of mobile robots, sensors are used as safety components to detect potential hazards and avoid collisions. Safety-related sensors must be parts that have been certified by standards (such EN 61508) that ensure a certain safety level because they are very relevant to the system's overall safety. EN 61508 requires that sensor used in safety-critical systems meet specific functional safety requirements which includes the identification of safety functions, the selection of safety hardware and software, and the implementation of safety measures such as redundancy, diversity and fault tolerance. Some common types of sensors used in mobile robots include 3D cameras [Son et al., 2019] which provide depth information and enable the robot to detect obstacles in its path. They can also be used to detect people and other objects in the robot's vicinity, for instance with ultrasonic sensors [Ohya et al., 1998] which emit high-frequency sound waves and measure the time it takes for the waves to bounce back. This information is used to detect the distance to an object and avoid collisions. Infrared sensors which detect heat emitted by objects and can be used to detect the presence of people or other warm objects in the robot's path. Laser scanners sensors emit a laser beam that sweeps across the environment, measuring the distance to objects in its path. This information is generally used to create a 3D map of the environment and detect obstacles. Additionally, laser sensors are a very common type of electromagnetic wave sensor. They are typically utilised for SLAM and frequently employed as a LiDAR system [Shen, 2021]. They provide mobile robots two advantages. It can first localise itself within its surroundings. Second, it is a successful method for avoiding obstacles. Ultrasonic sensors are the other sensor type. The fundamental operation is quite similar to a laser sensor, which detects the sensor's reflecting wave and figures out how long it took to get to the object and return. Ultrasonic sensors are very helpful for glass walls since laser or infrared is not reflecting for glass and can be detected. A disadvantage of ultrasonic sensors could be an annoying beat while calculating the distance to other objects [Siegwart et Nourbakhsh,2004]. Collaborative robots or cobots are designed to work alongside human workers. They are equipped with sensors and software that can detect the presence of humans and adjust their movements accordingly. Cobots can also be programmed to stop or slow down if they come into contact with a human worker, reducing the risk of injury [Achour et al., 2022].

2.2 Robust Navigation and sensor fusion

In addition to employing different type of sensors, mobile robots require reliable navigation. The localization of mobile robots, environment mapping, and path planning from one station to another are crucial components of reliable navigation [Gutmann, 2000].

Reliable navigation systems enable mobile robots to perceive and interpret their surroundings, plan and execute their movements, and avoid obstacles and collisions. These systems usually rely on various sensors, such as cameras, LiDARs, sonars, or even GPS, to gather information about the robot's environment. Once the robot has gathered this information, it can use it to create a map of its surroundings, localize itself within that map, and plan a safe trajectory to navigate to a target location [Wang et Herath, 2022]. This information is critical for ensuring the safety of the robot, as well as the safety of any people or objects in its vicinity. In addition, reliable navigation systems also play a crucial role in enabling mobile robots to perform complex tasks with high accuracy and efficiency. For example, a mobile robot equipped with a reliable navigation system can quickly and safely move from one location to another, pick up and manipulate objects with precision, and avoid collisions or other hazards along the way. Overall, reliable navigation systems are essential safety components for mobile robots, as they enable these robots to operate effectively and safely in complex environments, perform complex tasks with precision and efficiency, and avoid potential accidents or collisions that could cause damage or harm [Yun et al., 2018].

2.3 Software Safety

Software safety plays a critical role in ensuring the safety of mobile robots. Mobile robots rely heavily on software to control their movements, avoid obstacles, and interact with their environment. Any software errors or defects could potentially result in the robot operating unsafely, causing damage or injury. An open source software framework called the robot operating system (ROS) makes it simple to create robot applications [Quigley et al., 2009] and operate robot systems. The majority of mobile robot systems in use today employ the ROS framework because it offers a wide range of beneficial packages for various issues. As a result, an issue need not always be solved from scratch. In this framework, several sensors and actuators are preprogrammed and ready to use. See [Ahmed et Jang, 2018], [Fang et al., 2018] for examples of several localization and navigation techniques for mobile robots that were programmed using ROS. The fact that the two primary hardware components (mobile base and robot arm) are managed in one software framework makes utilising ROS with mobile manipulators safer than other methods.

3 SAFETY STANDARDS FOR MOBILE ROBOTS

Reconfigurable manufacturing systems (RMS) are characterized by their ability to rapidly and cost-effectively adapt to changes in product design, production volume, and market demand, utilizing modular and scalable components [Koren et al., 2018]. Within RMS, mobile robots can be used for tasks such as material handling, assembly, and inspection, enabling a high level of adaptability and responsiveness. However, incorporating mobile robots into RMS requires addressing specific safety concerns, such as collision avoidance between robots and other equipment during reconfigurations, communication and coordination with other devices in the system, and ensuring safe human-robot interactions when the manufacturing layout or processes change. [Sallez et al., 2020] present a framework for the design, evaluation, and optimization of RMS, which includes safety considerations for mobile robots in this context.

To ensure the safe operation of mobile robots in manufacturing settings, several safety standards and regulations have been developed. These standards provide guidelines for designing, testing, and operating mobile robots to minimize risks and prevent accidents.

It's critical to understand and abide by all rules and regulations related to mobile robots in industrial environments in order to obtain a safety certificated system. ISO 13482:2014 [Leuze, 2018] provides guidelines for the design, testing, and deployment of service robots, including mobile robots. It covers a range of safety aspects, such as obstacle detection, emergency stop, and human-robot interaction. Based on this standard, the robot manufacturer must perform a thorough assessment to identify potential hazards associated with the use of the robot. The risk assessment should consider factors such as the robot's mobility, its environment and its intended use. The robot must be designed with appropriate protective measures to reduce the risk of injury or harm to users which include safety sensors, emergency stop buttons and warning signals. The robot must be designed with appropriate operational requirements to ensure safe use which may include clear instruction for use, appropriate training for users and ability to monitor robot's operation. ISO 10218-2:2011 [DIN EN, 2011] specifies the requirements for the safe integration of industrial robots, including mobile robots. The standard requires that a risk assessment be conducted for each mobile robot application to identify and evaluate potential hazards and associated risks. The risk assessment must consider the robot's operating environment, including the terrain, obstacles, and proximity to humans and other equipment. The standard requires that mobile robots be equipped with safety functions that detect and mitigate hazards. These safety functions can include emergency stop buttons, protective barriers, warning alarms, and safety sensors that detect people or objects in the robot's path. The standard specifies requirements for the design of mobile robots, including structural integrity, stability, and performance in different operating conditions. The standard requires that mobile robot control systems be designed to prevent unintended motion and provide safe operation. The control system must also include safeguards against unauthorized access, tampering, or malicious use. These requirements include procedures for verifying safety functions, training operators, and conducting regular safety inspections. ANSI/RIA R15.08:2019 [DIN EN, 1997] covers the design, installation, and operation of industrial robots, including mobile robots. The standard requires that a risk assessment be conducted for each mobile robot application to identify and evaluate potential hazards and associated risks. The standard requires that mobile robots be equipped with safety functions that detect and mitigate hazards. These safety functions can include emergency stop buttons, protective barriers, warning alarms, and safety sensors that detect people or objects in the robot's path. The design must also consider the robot's ability to avoid collisions, navigate around obstacles, and operate safely in different environments. The standard requires that mobile robot control systems be designed to prevent unintended motion and provide safe operation. The control system must also include safeguards against unauthorized access, tampering, or malicious use. The standard specifies requirements for the interaction between humans and mobile robots, including requirements for safe distance, speed, and force of the robot's movement. The standard also includes guidelines for the design of interfaces, such as displays and controls, that facilitate safe interaction between humans and robots. The standard specifies requirements for the installation, maintenance, and repair of mobile robots. These requirements include procedures for verifying safety functions, training operators, and conducting regular safety inspections. IEC 61508:2010 [DIN EN, 2016] provides guidance on the functional safety of electrical, electronic, and programmable electronic systems. It is applicable to a range of industries, including robotics, and provides a framework for ensuring the safe design and operation of mobile robots. The standard requires that safety be managed throughout the entire life cycle of the system. This includes the establishment of a safety plan, the identification of safety-related requirements, and the implementation of safety-related measures. The standard specifies requirements for the design of the system architecture, including the selection and integration of safety-related components and subsystems. The design must ensure that safety is maintained even in the event of failures or malfunctions. The standard requires that the safety-related aspects of the system be verified and validated through testing, analysis, and other methods. This includes testing of safety functions, assessment of system behavior under fault conditions, and validation of safety-related software. The standard requires that documentation be prepared throughout the life cycle of the system, including safety plans, risk assessments, safety requirements, and verification and validation reports.

4 SAFETY MEASURES FOR MOBILE ROBOTS IN INDUSTRIAL ENVIRONMENTS

Several different safety ideas for mobile robots are covered in this part, and their appropriate use in various scenarios is also examined in industrial environments based on the author's analysis of papers and safety standards [Papa et al., 2018].

4.1 Safety rings

Safety rings are physical barriers that are typically installed around the perimeter of a mobile robot's workspace to prevent collisions with objects or people [Courtieu et al., 2022]. These rings are an important safety component of mobile robots because they help to prevent accidents and protect both the robot and its surroundings. If the robot does come into contact with the safety ring, sensors or switches built into the ring can detect the impact and trigger an emergency stop or other safety mechanism to prevent further movement. Safety rings can be made from a variety of materials, including metal, plastic, or even fabric, depending on the specific application and environment. They can also be customized to fit the specific shape and size of a mobile robot's workspace, which helps to maximize the protection they provide [Millet et al., 2014]. In addition to preventing collisions, safety rings can also be used to define the boundaries of a mobile robot's workspace and prevent unauthorized personnel from entering the area. This helps to further enhance the safety of the robot and its surroundings by ensuring that only trained personnel with the proper equipment and safety gear are allowed within the robot's workspace [Thrun et al., 2005]. However, the drawback of using safety rings is that this approach greatly limits the deployment as the worker aren't allowed inside that workspace anymore and furthermore collaborative tasks are not possible.

4.2 Obstacle avoidance

Obstacle avoidance is a key safety component of mobile robots, as it helps to prevent collisions with objects or people in the robot's path [Chi et al., 2011]. With obstacle avoidance technology, mobile robots can detect and avoid obstacles in their path including people and navigate through complex environments more easily, reducing the need for human operators to manually guide the robots. Also, obstacle avoidance sensors can provide mobile robots with real time information about their surrounding including location of people and obstacle which can help to enhance the situational awareness of both he robot and any human operator [Medina-Santiago et al., 2014]. By avoiding obstacles and navigating more efficiently, mobile robots can complete tasks more quickly and with greater accuracy which helps to reduce the amount of time workers need to spend in hazardous areas in exposure to potential risks.

There are various methods for obstacle avoidance in mobile robots, including the use of sensors, mapping algorithms, and path planning techniques. One common approach to obstacle avoidance is to use sensors, such as LiDARs or sonars [Wu et al., 2015], to detect objects in the robot's path. These sensors can provide information about the distance and location of obstacles, which can be used to adjust the robot's trajectory or speed to avoid collisions.

Another approach to obstacle avoidance is to use mapping algorithms to create a map of the robot's environment. This map can then be used to plan a safe path for the robot to navigate to its destination, taking into account any obstacles that may be in its path. Path planning techniques can also be used to help mobile robots avoid obstacles. For example, the robot can use a technique called "potential fields" to calculate the forces acting on it based on the location and distance of nearby obstacles. This information can then be used to adjust the robot's trajectory and speed to avoid collisions. In addition to these techniques, there are also advanced methods for obstacle avoidance that use machine learning or artificial intelligence algorithms to enable the robot to learn from its past experiences and improve its obstacle avoidance capabilities over time.

4.3 Tactile sensors

Tactile sensors are another important safety component of mobile robots as they can help the robot to detect and respond to contact with objects or people in its environment [Bogue,2020]. These sensors can provide information about the force and pressure of contact, which can be used to adjust the robot's trajectory. Tactile sensors can be placed on the surface of the robot's end effector or on other parts of the robot's body, such as its arm or torso. These sensors can be designed to detect a range of forces and pressures, from light touches to heavy impacts. When the robot comes into contact with an object or person, the tactile sensors can detect the force and pressure of the contact, which can be used to adjust the robot's behavior. For example, if the robot comes into contact with a person, the tactile sensors can detect the force of the contact and trigger an emergency stop or other safety mechanism to prevent the robot from causing harm. Tactile sensors can also be used to provide feedback to the robot's controller, which can be used to adjust the robot's trajectory or speed to avoid collisions or reduce the force of contact. This can help to prevent damage to the robot or its surroundings and improve the robot's overall safety and performance. [Siegwart et Nourbakhsh,2004].

4.4 Safe navigation for mobile robots

Maybe a safety ring cannot be implemented because of financial or space limitations. Providing a robust and safe navigation strategy could be a suitable alternative for safety of mobile robots in this situation [Bouraine et al., 2012]. The navigation stack must first create a map of the robot's environment. This can be done using sensors such as laser scanners, cameras, or sonar sensors. The map should be created with high accuracy and detail, and should include information about obstacles, terrain, and other features of the environment [Li et al., 2018]. Once the map is created, the navigation stack can plan a safe path for the robot to follow. The path planner takes into account the robot's current location, destination, and the map of the environment. It uses algorithms to find the shortest and safest path to the destination. The navigation stack uses motion control algorithms to move the robot along the planned path. The motion controller receives input from the robot's sensors, such as odometry or GPS, to determine the robot's current position and orientation. It then adjusts the robot's velocity and steering angle to follow the planned path. The navigation stack also includes a localization component, which uses sensor data to estimate the robot's position and orientation in the environment. This information is used to update the map and to improve the accuracy of the path planner and motion controller. The navigation stack can include a route management component. This component stores information about safe routes that have been previously planned and verified. When the robot needs to navigate along a safe route, the route management component selects the appropriate route from the database and provides it to the path planner. The research fields of self-localization, map construction, and path planning can be used to categorise the robust navigation of mobile robot systems [Gutmann, 1999]. However, it is important to differentiate between an autonomous mobile robot (AMR) and an automated guided vehicle (AGV) first. AMRs can navigate the surroundings dynamically without the need for a predetermined track. A robot can plan its own route through the factory by using a map that has been either automatically created (SLAM) or stored inside the robot. Furthermore, since only the map needs to be updated, expanding or changing the work region is simple. An AGV needs "tracks," in the shape of lines or figures on the floor, in contrast to the AMR. Therefore, expanding or changing the job area is more difficult and time-consuming. As a result, the AGV can only follow predetermined routes and must stop at any obstacles without being able to alter its course [MIR, 2017]. This section will provide a summary of potential navigation techniques.

4.4.1 Guidpath following

Guidepath following is a method most AGVs are using. Most AGVs follow guides, which is a technique. Because the robot follows strictly a predetermined path, the technique is very straightforward and inexpensive. The path could be as basic as a piece of adhesive tape on the ground. The large glass fronts might be an issue because optical line sensors use light to detect the adhesive tape. Magnetic tape on the floor could be used to get around this issue with magnetic line markers. Because the AMR cannot get lost and a central PC always knows where the robots are, a large number of them could operate without incident in the same factory using this technique. The inflexibility of this approach is its main flaw. Every new route needs to be taped on the floor, and the system's digital representation needs to be updated. However, since the flexibility of the AMR path planning and obstacle avoidance is not desired, this drawback for an AMR could be the ideal answer for safe navigation.

4.4.2 Grid Localization

Grind localization is an important capability for mobile robots in manufacturing, especially those that are involved in tasks such as grinding, polishing, or deburring. Grid localization involves the ability of a mobile robot to accurately and precisely position itself relative to a workpiece, even when the workpiece is moving or the robot is subjected to external disturbances [Panigrahi et Bisoy, 2022].

There are several techniques that can be used to achieve grind localization for mobile robots including Sensor-based localization, Beacon-based localization, Machine vision-based localization, Inertial navigation and Global positioning system (GPS).

Sensor-based localization involves using sensors, such as cameras or laser scanners, to detect the position and orientation of the workpiece and the robot. This information is then used to calculate the relative position of the robot with respect to the workpiece.

In Beacon-based localization technique beacons or markers are placed on the workpiece or in the environment, and the robot uses these markers to determine its position and orientation. This technique can be very accurate, but it requires that the beacons be visible to the robot at all times.

In Machine vision-based localization Machine vision techniques can be used to analyze images of the workpiece and the robot to determine their relative positions. This technique can be very accurate, but it can be affected by changes in lighting or the appearance of the workpiece.

Global positioning system (GPS) can be used to track the position of the robot and the workpiece. This technique is less accurate than other techniques, but it can be useful in outdoor environments or in large manufacturing facilities.

By implementing one or more of these techniques, mobile robots can achieve accurate and reliable grind localization, which can improve the quality and efficiency of the manufacturing process. It is important to choose the most appropriate localization technique based on the specific requirements of the manufacturing process and the environment in which the robot will operate.
This navigational technique is employed by the "Amazon Kiva Robots" and the "Alibaba Quicktron Robots." There will be a grid of QR-Codes affixed to the floor or ceiling, and there should be very little space between each QR-Code. These QR-Codes, which record the label and location in the factory, are being scanned by mobile robots. For accurate scans, industrial cameras are used, and they will extract the robot's drift as well as location and orientation. With the distance of a safety encoder, the robot can now rectify the drift and proceed to the next QR-Code.

4.4.3 Multilateration

Multilateration is a technique used for safe navigation of mobile robots that involves determining the position of the robot by measuring the distance to several known reference points in the environment. It is a form of localization that uses multiple distance measurements to triangulate the robot's position. In multilateration, the robot carries a receiver that can detect signals from reference points, which can be radio beacons or other devices that emit signals at known frequencies. The receiver measures the time it takes for the signals to reach the robot and calculates the distance to each reference point based on the speed of the signal. Once the distances to several reference points are known, multilateration can be used to determine the robot's position. This is done by intersecting spheres with radii equal to the measured distances around each reference point. The intersection points of the spheres represent the possible positions of the robot, and the true position can be determined by selecting the intersection point that is closest to the actual position. Multilateration is a useful technique for safe navigation of mobile robots because it does not rely on external infrastructure such as GPS or a pre-existing map of the environment. It can be used in environments where GPS signals are weak or not available, or in situations where the environment is changing rapidly and a pre-existing map is not accurate. However, multilateration has some limitations. It requires a sufficient number of reference points to provide accurate position estimates, and the accuracy can be affected by the geometry of the environment and the quality of the signal measurements. In addition, it may be affected by interference from other devices or signals in the environment. Nonetheless, multilateration remains a valuable tool for safe navigation of mobile robots in a variety of applications.

5 BENCHMARKS AND TEST PROCEDURE FOR THE SAFETY OF MOBILE ROBOT

A test procedure for the safety of a mobile robot typically involves verifying that the robot and its control system meet the safety requirements of relevant standards and regulations.
Test the emergency stop feature: Verify that the robot's emergency stop feature works as expected by pressing the emergency stop button or activating the emergency stop mechanism. Verify that the robot stops moving immediately and that any active tasks are halted.
Test the motion control system: Verify that the robot moves smoothly and without unexpected movements. Test the robot's speed, acceleration, and direction control to ensure that it moves safely and predictably.
Test the collision detection and avoidance system: Verify that the robot detects obstacles and other robots and takes appropriate action to avoid collisions such as such as changing its speed or direction, to avoid the obstacle. Test the robot's behavior when approaching obstacles or other robots and ensure that it stops or maneuvers around them.
Test the task execution control: Verify that the robot performs its intended tasks safely and correctly which is ensuring that the robot can operate in its intended environment without posing a threat to humans, animals, or property. This involves testing the robot's safety features, such as its sensors and emergency stop mechanisms, to ensure that they function properly and can detect and respond to potential safety hazards.
Test the system integration: Verify that all components and subsystems of the robot are properly connected, calibrated, and synchronized. Test the robot's behavior under different operating conditions to ensure that all components work together as expected.
Suppose a mobile robot is being developed for use in a warehouse environment. The robot is designed to transport goods from one location to another and is equipped with a collision detection and avoidance system, an emergency stop feature, and a task execution control system. Here is an example of how the test procedure might be applied:
Press the emergency stop button and verify that the robot stops moving immediately and that any active tasks are halted. Test the robot's speed, acceleration, and direction control by commanding it to move to various locations in the warehouse. Verify that the robot moves smoothly and without unexpected movements. Place obstacles and other robots in the robot's path and verify that the robot detects them and takes appropriate action to avoid collisions. Test the robot's behavior when approaching obstacles or other robots and ensure that it stops or maneuvers around them. Program the robot to transport goods from one location to another and verify that it performs the task safely and correctly. Test the robot's behavior when transporting goods and verify that it does not cause damage or injury. Test the robot's behavior under different operating conditions, such as different lighting conditions or floor surfaces, to ensure that all components work together as expected.
By following this test procedure, developers can ensure that the mobile robot is safe for use in the warehouse environment and meets the safety requirements of relevant standards and regulations.

6 FUTURE TRENDS IN MOBILE ROBOT SAFETY

The future of mobile robot safety in manufacturing is focused on creating collaborative and intelligent robots that work alongside human workers while minimizing the risk of accidents. Manufacturers will continue to innovate and invest in new technologies to enhance the safety of mobile robots in manufacturing.
The other useful strategy is using AI. AI and machine learning can be used to enhance the safety of mobile robots in manufacturing [Zöldy et al., 2020]. For example, AI algorithms can analyze data collected from sensors to detect potential hazards and adjust robot movements to avoid those hazards. Machine learning can also be used to improve the accuracy of robots in detecting and avoiding obstacles [Zhu et Hayashibe, 2022]. Despite the advantages of using AI-based strategies, they are still complex to guarantee that the behavior

will be perfectly reproductible. This is because AI methods are often designed to learn and adapt their behavior based on data and feedback from the environment. As a result, the behavior of an AI-based mobile robot may change over time as it continues to learn and adapt. Standardization of safety protocols and regulations for mobile robots in manufacturing is another strategy which can improve safety and reduce the risk of accidents [Zou et al., 2022]. Manufacturers can adhere to established safety standards and regulations, which can help them design robots that are safe for use in manufacturing plants. Additionally, Remote monitoring of mobile robots can help identify potential hazards before they result in accidents. Remote monitoring can also be used to monitor the health of robots and ensure that they are operating safely and efficiently [Zhou et al., 2022].

In terms of the evolution of safety standards for mobile robots in manufacturing, it is likely that standards will need to be revised and updated as new technologies and applications emerge. As mobile robots become more advanced and integrated into the manufacturing process, new safety concerns may arise that require additional regulations and protocols. Similarly, the use of AI in mobile robots raises ethical issues [Lin et al., 2011] related to accountability and transparency. As mobile robots become more autonomous, it may be difficult to determine who is responsible in the event of an accident or malfunction. As such, it is important for manufacturers to consider the ethical implications of using AI in mobile robots and to develop clear guidelines and protocols to ensure accountability and transparency.

Incorporating safety best practices for mobile robots within reconfigurable manufacturing systems requires addressing the unique challenges associated with these environments. This includes developing adaptive collision avoidance algorithms that can account for changes in equipment and layout during reconfigurations, and designing communication protocols that ensure seamless coordination between mobile robots and other devices in the system. Additionally, implementing robust human-robot interaction (HRI) safety mechanisms, such as dynamic safety zones and real-time monitoring of human presence, can minimize risks when the manufacturing environment is modified. Manufacturers should also consider using machine learning techniques to predict and optimize the safety of mobile robots as they adapt to different tasks and configurations. By addressing these technical challenges, manufacturers can ensure the safe and efficient operation of mobile robots within reconfigurable manufacturing systems.

7 CONCLUSION

In conclusion, ensuring that mobile robots meet the highest safety standards is crucial to prevent accidents or injuries in the field. In this review paper, we have recommended several benchmark and test procedures to verify that mobile robots comply with relevant safety standards and are safe to use in various operating conditions.

These benchmark and test procedures include conducting a hazard analysis, complying with safety standards, performing functional safety testing, simulation testing, field testing, and implementing a continuous monitoring system. By following these procedures, mobile robot manufacturers and operators can ensure that their machines are safe and reduce the risk of accidents or injuries.

In addition, we have emphasized the importance of designing mobile robots with safety in mind from the outset and ensuring that they comply with relevant safety standards. This includes implementing multiple safety sensors, emergency stop buttons, safety interlocks, and user-friendly interfaces that prioritize safety.

Overall, this review paper highlights the importance of benchmark and test procedures in verifying that mobile robots meet the highest safety standards. By following these procedures and designing mobile robots with safety in mind, we can ensure that these machines are safe and reliable in various operating conditions.

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