Chapter 5
A Brief Review of Robotic Welding Technology for Structural Steel Applications

Ahmad Rababah, Feras Abla, Sahabeddin Rifai, Guilherme Pereira, Devin Huber, and Onur Avci

Abstract The increasing demand for faster and more economical construction of steel structures has positioned welding as a crucial element in both shop fabrication and site erection. This paper presents a brief summary of the application and feasibility of robotic technologies for automating the welding process. Welding is a cornerstone of modern steel construction, facilitating the connection of steel members for the creation of robust and durable structures. Due to the efficiency and significant contributions of stationary robotic welding systems and robotic welding arms, these technologies are expected to gain widespread popularity and become essential in the steel and metal industries. Well-aligned with the American Institute of Steel Construction's (AISC) "Need for Speed" initiative, robotic welding has the potential to bridge the gap between the industry's demand and the available qualified welders in the structural steel industry. This paper reviews the development of robotic and wall-climbing robot technologies, as well as the associated controlling tools such as sensors, cameras, GPS receivers, and simultaneous localization and mapping (SLAM) systems. These advancements indicate that robotics technologies are sufficiently advanced for implementation in structural steel applications at construction sites, with numerous autonomous robots having been designed and developed over the past decades.

Keywords Structural steel · Welding · Collaborative robots · Automated welding · Robotic welding

Introduction

The growing emphasis on reducing hazards and risks to individuals, enhancing productivity and efficiency, and optimizing both time and costs has led to the development and implementation of advanced technologies designed to assist with

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human tasks in manufacturing and industrial sectors. In the United States, and most other countries, the majority of structures, including bridges, high-rise buildings, and power and petrochemical plants, are typically constructed using structural steel. Recently, the steel shear wall system has been introduced as an effective alternative to conventional lateral load-resisting systems in the construction field. This system offers advantages such as a lighter structure, quicker construction, and superior quality compared to traditional reinforced concrete structures [1]. In addition, the implementation of continuous columns and interconnected column-beam systems is essential for maintaining structural integrity and ensuring optimal performance under various loading conditions and environmental circumstances. Components within a structure are often joined using bolts or welding techniques, including column splice welding and the welding of shear wall systems with steel frames. These methods effectively transfer vertical and horizontal loads between the connected elements. Welding, in particular, is a fundamental component in structural steel construction, enabling the creation of strong and durable structures. The automation of such an important component with mobile robots aligns with the American Institute of Steel Construction's (AISC) ”Need for Speed” initiative, which emphasizes the importance of efficient and rapid construction methods.

In general, welding is a process of joining metals together using pressure or heat on the filler metal, in some methods, and workpiece to form the weld that can substitute the mechanical fastener connections. More than eighty different methods are used to achieve the welding [2]. Welding, brazing, and soldering are joining metal methods with different procedures. Brazing and soldering are characterized by melting the filler metals, but not the base metals as in the welding case. Neither brazing nor soldering is used for structural steel connections; as an alternative, welding is an appropriate option that offers the strongest joint to support the load. Typically, the welded section of a joint shows a greater strength than the base or original metal. However, imperfections that arise during or after the welding process, whether internal or external, can compromise the weld's performance and weaken the joints between metal components. Identifying and assessing these defects is crucial for ensuring quality control, thereby enhancing the weld's ability to perform its expected function effectively. Welding field-related workers need to comprehend the prevalent problems associated with welding in structures like causes, effects, and outcomes. Regulations and standards set by the American Welding Society (AWS) [3], are essential to guarantee the integrity and quality of weldment. Furthermore, the detection and inspection of defects are essential for addressing unacceptable defects that could affect the structural reliability of a welded structure. External defects, such as cracks, undercuts, overlaps, porosity, and spatters, are visible on the surface of the weld and can be detected by the human eye. Conversely, internal defects, which include incomplete penetration, inclusion, and lack of fusion, occur within the welding joint and are not visible to the naked eye. Detecting these internal defects requires specific methods including Non-destructive testing (NDT) [4], and destructive testing (DT). NDT can recognize the defects in welding by examining the workpiece without harming it or affecting its strength and reliability. Some of these tools and methods used in NDT are ultrasonic test (UT), radiography test (RT), electromagnetic test, eddy current test (ET), magnetic particle test (MT), acoustic emission (AE), dye penetrant (PT) and leak testing (LT). On the other hand, DT studies and tests the material or welded workpiece with some damages or destructions left on it, typically, such tests are conducted on small workpieces at the initial stages of the process, before welding and fabricating larger components. This approach enables an understanding of how the material will perform under various stress conditions.

Gas Metal Arc Welding (GMAW) and Gas Tungsten Arc Welding (GTWA) have traditionally been the most employed in robotic welding applications due to their compatibility with robotic systems [5]. However, developments in welding technology have expanded the range of methods engaged in robotic welding such as laser welding, plasma welding, metal inert gas welding, and spot resistance welding. A robotic welding system typically contains several critical components, including a mobile platform, manipulator, controller, welding torch, and an array of sensors. The mobile platform, or robotic base, serves as the primary structural frame of the system, supporting all other components and providing the capability to move, climb walls, and maneuver around obstacles. The manipulator is tasked with the precise movement and positioning of the welding torch, ensuring high-accuracy welding operations. Acting as the system's central intelligence, the controller processes input from the sensors and executes pre-programmed welding routines. This sophisticated organization of components not only enhances the precision and efficiency of welding tasks but also allows for real-time adjustments and optimization of welding parameters. In addition, the sensors play a crucial role in monitoring various parameters such as temperature, alignment, and weld quality, providing real-time feedback to the controller to ensure optimal performance and adjust parameters as needed [6].

Performing the welding tasks by using an automated system or robotic manipulator (arm), first developed by a Japanese company, Kawasaki in 1974 and used in the manufacturing of motorcycles has revolutionized the industry [7]. These automated systems offer numerous advantages, including enhanced productivity, improved quality, increased safety, and significant time and cost savings. Additionally, robotic welding systems can operate under extreme conditions, such as high temperatures and high pressures, which pose substantial risks to human workers, especially those working at high elevations in structural steel construction.

Robotic Welding

Robotic welding manipulators have achieved widespread adoption and have become the industry standard in manufacturing and related sectors. Initially designed as stationary-mounted robots, welding robots became highly popular in industries with active production lines and substantial welding tasks, such as metal fabrication, aerospace, and automotive manufacturing. These robots are programmed to perform repetitive tasks with high levels of accuracy and consistency, following predetermined routines that specify the direction, distance, velocity, acceleration, and deceleration of coordinated motion sequences [8]. This precision and reliability make robotic welding an ideal solution for high-volume production environments.

The implementation of robotic welding in the construction field offers significant advantages. One of the primary benefits is addressing the gap between the demand for skilled welders and the available workforce, a global issue highlighted by the American Welding Society (AWS). By deploying robots, the construction industry can mitigate this shortage, ensuring projects are completed efficiently and on schedule. Additionally, robotic welding enhances the quality and consistency of welds, reduces human error, and improves overall safety on construction sites. This technological advancement not only meets the immediate labor needs but also supports the industry's long-term goals of productivity and innovation. In addition, using innovative systems and technologies in the construction field contributes to the optimization of resources and reduction of waste, supporting the industry's commitment to sustainable development.

In the second stage of development, the stationary welding arm was advanced to create a more user-friendly, collaborative welding robot, commonly known as a ”Cobot”. In contrast to traditional welding arms, Cobots prioritize harmonious interaction between humans and robots, with a strong emphasis on safety and collaboration. These robots are equipped with advanced sensors, force and torque detection, and responsive performance features to ensure safe and effective human-robot interaction. The core idea behind this collaboration is to merge human creativity and decision-making abilities with cutting-edge technological systems. This interaction aims to advance a more innovative, efficient, and adaptable industrial environment, ultimately enhancing productivity and workplace safety [9]. The collaboration between Cobots and humans is facilitated through the application of machine-learning tools that control and train robots [10]. By leveraging machine learning and other decision-making algorithms, Cobots can learn from human actions, adapt to various tasks, and detect human moves which provides a safer environment to enable Cobots to work alongside human operators more effectively, enhancing precision and efficiency in welding operations. Generally, cobots are smaller in size compared to the traditional arms and designed for lighter repetitive welding tasks, more cost-effective, versatile, and simpler programming and reprogrammed for different tasks. Recently, several companies were able to develop collaborative welding robots such as the Cooper welding cobot which was designed by Lincoln Electric [11], the Copilot Cobot by Miller Electric [12], and the Cobot by ESAB [13]. The primary role of human welders collaborating with Cobots is to supervise the operational processes, ensure the quality of the welds, and make essential adjustments to the Cobots' programming to execute precise welding tasks [10].

Wall-Climbing Robots and Sensor Technologies

The current vision focuses on developing smaller autonomous robots capable of performing welding tasks in various locations and under different conditions. Over the past few decades, significant advancements have been made in creating wall-climbing robots, resulting in the emergence of hundreds of prototype systems. These innovations pave the way for designing specialized welding robots, capable of navigating and operating in challenging environments. For a welding robot, the payload is critical, alongside mobility, as the robot must be able to carry both the welding equipment and the manipulator. Considering that welding will be performed on ferromagnetic surfaces, and given the stability, smooth mobility, and lightweight nature of wheeled robots compared to legged robots, the use of wheeled robots is recommended and widely adopted for wall-climbing applications. Magnetic wheeled robots are particularly suitable for this purpose. These robots can adhere to and navigate vertical and inclined surfaces efficiently, making them ideal for welding tasks in such challenging environments. The adoption of magnetic wheeled robots in welding applications not only enhances operational stability and precision but also expands the scope of automated welding to include complex and hard-to-reach areas. In 1995, the Kansai Research Institute developed dual magnetic wheels to address the challenge of traveling on discontinuous surfaces and pipes with bending joints, passively without any external source of energy [14]. Electromagnetic wheels can mitigate some limitations associated with permanent magnetic or passive mechanisms, such as the ability to navigate sharp obstacles or transition between different or perpendicular surfaces. When using passive systems, the robot may be trapped in corners due to the equivalent of magnetic forces from both surfaces. To address this issue, an active magnetic wheel mechanism was developed, incorporating a controlled lifter-stabilizer that facilitates climbing and traversing obstacles such as perpendicular surfaces [14]. Eto and Asada designed a wall-climbing robot for welding which uses two free rocker-arm hovering mechanisms that have magnetic spherical wheels. It can navigate obstacles that are 50 mm high and 90-degree corners [15]. Wu et al. developed a wall-climbing welding robot with non-contact permanent magnetic adhesion. Where the magnetic suckers are positioned beneath the axles with an adjustable gap, this design significantly enhanced the robot's performance [2]. In 2022 Zhang et al. improved the flexibility and stability of the robot by replacing the contacted traditional magnetic circuit on the wheels with a newly designed permanent magnetic chuck [16], which has been proven to increase the adsorption force by 9% compared to the traditional magnetic circuit [17]. A design of three divided body parts connected with flexible joints and a six-wheel robot was proposed to provide more motion flexibility and the ability to maneuver and travel through convex and concave surfaces, wall and ceiling climbing robot [18]. Franko et al. in 2020 designed a magnetic wall climbing robot, highly effective for turbine maintenance, a robot was provided with a LiDAR vision sensor for inspection and a fixed mainframe with a non-contact magnet to a climbed surface and rotating wheels to provide motion capability to the robot [1].

Moreover, various robots utilizing different technologies are currently available in the market. For instance, Sumitomo Heavy Industries, a Japan-based company, introduced a magnetic spherical wheeled climbing robot in 2022. This robot is capable of navigating ferromagnetic structures on vertical, horizontal, and curved surfaces. However, its traveling and climbing mechanisms are constrained by the material and shape of the surfaces it climbs [19]. In 2021, Gecko Robotics, a United States located company, successfully developed the latest advanced robot, the TOKA Flex, from the Toka series. This cabled robot is designed to inspect and gather data on ferromagnetic surfaces and was primarily created for application in industrial plants to perform non-destructive testing (NDT) inspections. This is achieved through the utilization of an ultrasonic transducer, which is specifically designed for inspecting pipes and tanks. Toka Flex can climb 75 ft in height and can climb pipes 6 in diameter by using its four magnetic wheels [20]. Furthermore, for any smooth non-ferromagnetic surfaces such as glass, plastic, and aluminum. The world's first non-magnetic climbing inspection robot was developed in New Zealand by Invert Robotics Company [21] which developed a series of climb robots that work for non-ferromagnetic surfaces by using multiple systems like sliding suction adhesion, adhesion pads, vacuum pumps, and magnetic systems.

(a) (b)

Fig. 1 (a) Sumitomo Heavy Industries climbing robot [19]. (b) The TOKA Flex Robot [20].

To effectively operate welding robots, a comprehensive array of devices and equipment is essential, including an Inertial Measurement Unit (IMU), GPS receiver, and multiple cameras, mounted on the manipulator. Additionally, tactile sensors and encoders on each servo joint are crucial components of the robot's instrumentation. These devices facilitate real-time control, enabling precise and efficient operation. For precise robot localization, a simultaneous localization and mapping (SLAM) system can be employed, which integrates data from both inertial sensors and cameras. This approach significantly enhances the robot's ability to navigate and map its environment with precision [22]. SLAM systems allow a robot to plan a course through an unfamiliar environment while simultaneously identifying its location within that environment. To execute the SLAM process, robots must be equipped with a range of sensors to gather various measurements along their trajectories. The primary sensors utilized include cameras, LiDAR, Global Navigation Satellite System (GNSS), and IMU. When a SLAM algorithm mainly uses camera sensors, it is termed visual SLAM, whereas the use of laser scanners characterizes it as LiDAR SLAM [23]. Particularly, LiDAR SLAM enables robots to progressively determine their movement by matching scanned 3D points as they navigate. During their journey, robots estimate the distance traveled to determine their current position. Simultaneously, they generate a map of their environment by aligning these scanned points, typically utilizing the

Iterative Closest Point (ICP) algorithm to refine this alignment and enhance the accuracy of both the map and their positional estimates [24]. However, to achieve effective automated welding, it is essential to have an appropriate pre-trained program to ensure that the welding process can be monitored in real-time by various sensors. These sensors, integrated with software and neural networks, play an important role in controlling process parameters and predicting whether the final weld will be acceptable or defective. If the modeling predicts a potential defect during the welding process, it must intervene to adjust the process parameters and prevent any defects from occurring.

Overview of Mobile Robots in the Market

In recent decades, there has been a significant surge in the development and deployment of autonomous mobile robots. These robots have seen widespread application across various industries, including construction, agriculture, service, medical, and manufacturing sectors, among others. This growth is driven by developments in sensor technology equipped with onboard artificial intelligence and machine learning tools, which have enhanced the capabilities of these robots, enabling them to perform complex tasks with increasing efficiency and precision.

Mobile Welding Robots

In particular, the field of welding has seen numerous companies start the development of automated welding robots. Several countries have emerged as leaders in this endeavor, making significant progress in the advancement of robotic welding technology. The SIASUN company (based in China) has engineered a variety of mobile robots for various applications, including assembly, forklift operations, and material transfer. In 2024, SIASUN further expanded its robotic solutions by introducing a welding robot, including combined functionality in robotics, 3D vision, SLAM navigation, and artificial intelligence to develop the robot [25]. Moreover, for welding tasks, the O-Matic Corporation (based in China) has developed a mobile welding robot that integrates a mobile robotic platform featuring a 6-axis collaborative robot, alongside a welder and a water cooler. This sophisticated robot is capable of navigating construction sites with precision and executing welding tasks according to pre-programmed trajectories [26].

Additionally, Alpha Laser (based in the USA) company, was able to design the AL-ROCK Mobil, a highly advanced mobile robot equipped with a 4-kW laser, specifically designed for surface metal hardening and welding with wire or powder [27]. This system is fully mobile, as all essential components, including the laser, cooler, and robot controller, are integrated within the robot mobile frame. The Construction Innovation and Technology Fund (CITF) (based in China) has introduced the Welbot, an on-site mobile welding robot featuring advanced control software [28]. This innovative system is capable of auto-generating weld paths, performing 3D welding weaves, and managing complex, non-linear welding trajectories. Additionally, in Germany, the Intelligent Mobile Systems Lab (IMSL) is engaged in a project scheduled for completion in 2024, aimed at developing an omnidirectional manipulator for a mobile robot welding system. This innovative setup consists of an omnidirectional mobile platform and a robot arm that collaboratively performs continuous movements. The system is designed for various tasks such as spray painting, welding, and validating parts [29].

Mobile Robots in Diverse Sectors

In the construction field, a wide range of robots have been developed to perform various specialized tasks. These include robots designed for painting, drilling, welding, and cutting, as well as those intended for management and supervising purposes, Dusty Robotics, based in California, has developed the FieldPrinter 2, a state-of-the-art autonomous layout robot designed to revolutionize on-site performance, efficiency, and productivity [30]. This next-generation innovation features a compact design and enhanced capabilities, signifying a substantial advancement in construction automation technology. Okibo has proposed a mobile multi-purpose autonomous robot adapted for construction sites, an autonomous finishing robot. including wall plastering tasks, such as stucco, EIFS, concrete, primer, and adhesives [31]. In 2020, Hilti introduced its first robot, Jaibot, designed for semi-autonomous mobile ceiling-drilling operations. This cordless system offers ease of use, achieves precise indoor localization, and conducts dust-controlled drilling activities [32]. Moreover, the ”CAMERA” project (Construction And Manufacturing Enabled by a Mobile Robotic Arm) represents a collaborative effort between ABB, HAL Robotics, Skanska, and InnoTech UK in developing this robotic system. The robot consists of three distinct components: a mobile base, a scissor lift, and a robotic arm manipulator designed to maneuver tools. Tool paths are generated from a CAD model, while a localization system guides the robot to ensure precise execution of tasks, as it was engineered to perform a range of construction activities [33].

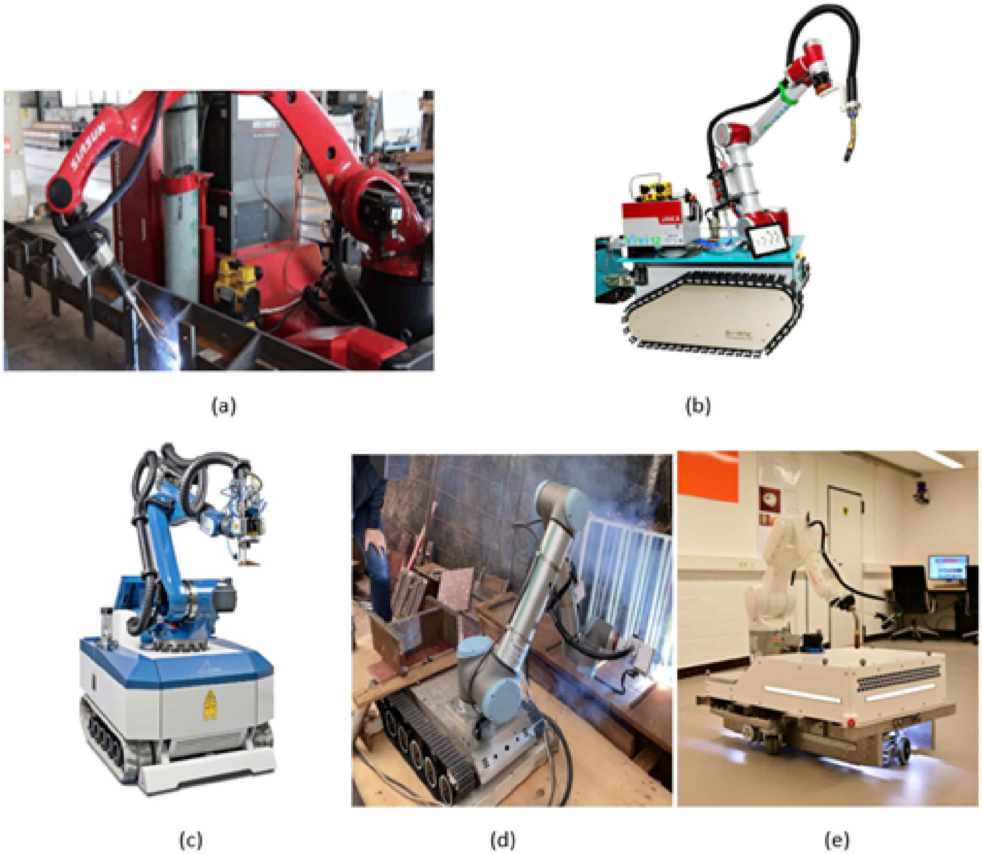

Fig. 2 (a) SIASUN robot [25]. (b) O-Matic robot [26]. (c) AL-ROCK robot [27]. (d) CITF Welbot robot [28]. (e) IMSL Project [29].

LiDAR-Equipped Mobile Robots

As discussed in Section 3, the implementation of advanced sensors and cameras is essential for the effective control and operation of autonomous robots. Doxel's LiDAR-equipped robots, for instance, capture comprehensive visual and spatial data of construction sites, providing detailed reports to project teams [34]. Similarly, the University of Edinburgh's TrimBot2020 utilizes a camera, stereo 3D vision technology, and LiDAR for autonomous pruning of roses and bushes, enabling the robot to recognize and distinguish between plant parts and ensure safe and efficient operation [35].

Furthermore, the Technical University of Darmstadt's Team Hector has developed a variety of robotic systems for search, rescue, and emergency purposes. These robots demonstrate proficiency in generating real-time 3D environmental maps, facilitated by a rotating Velodyne VLP-16 LiDAR for creating detailed 3D point clouds, complemented by an omnidirectional camera and an RGBD camera [36]. By combining these sensors and technologies, these autonomous robots can effectively navigate and operate in diverse environments, providing valuable data and services to their respective fields.

Challenges and Discussion

Despite the shortage of skilled welders, as reported by the American Welding Society (AWS), there are significant concerns about automating welding jobs with robots. Critics argue that robots will replace human welders, thus reducing job opportunities. However, it is essential to clarify that even with the deployment of welding robots, these machines cannot perform the entire task autonomously. Skilled experts are still needed to oversee, control, and make critical decisions during the welding process. Therefore, the role of human welders will evolve rather than disappear, with a greater emphasis on supervisory and decision-making responsibilities. This collaboration between human expertise and robotic efficiency can lead to enhanced

(a) (b)

(c) (d)

Fig. 3 (a) Dusty FieldPrinter2 robot [30]. (b) Okibo finishing robot [31]. (c) Hilti drilling robot [32]. (d) CAMERA robot [33].

productivity, job quality, and improved worker safety in the welding industry in addition to addressing the labor shortage issue. Moreover, it offers mutual benefits, enabling companies to meet production demands more effectively and providing skilled welders with opportunities to focus on higher-level tasks such as supervision and decision-making, rather than manual welding tasks.

Furthermore, the power supply for mobile robots is a crucial consideration in their design. Typically, most of the wall-climbing robots have been powered either by linking them to tethers or by using built-in batteries. Tethers also help with safety, however, restrict the robot's accessibility and the height of surfaces it can climb. Conversely, batteries also pose limitations due to their limited operation time. Currently, there are no small-sized batteries that offer extended operation times; larger or heavier batteries increase the robot's weight, leading to additional challenges like the weight of the robot. This is a critical factor, as it affects the robot's payload capacity, which must accommodate essential tools such as the torch, manipulator, and welding equipment. Furthermore, the robot's ability to climb surfaces and its stability depends on its weight and the strength of its climbing mechanism, which might utilize magnetic or electromagnetic wheels. The strength and characteristics of the surfaces the robot climbs are also valuable considerations. Balancing these factors is key to designing an effective and efficient mobile robot capable of performing complex tasks in various environments. Self-powered or power-harvesting solutions can be a significant step toward solving the power supply problem for mobile robots, offering increased flexibility and mobility. By harnessing energy from the environment or through innovative self-charging mechanisms, these solutions can extend the operational time of robots without the need for heavy or large batteries in addition to enabling robots to navigate and operate more freely, without the limitations imposed by tethers or frequent recharging requirements.

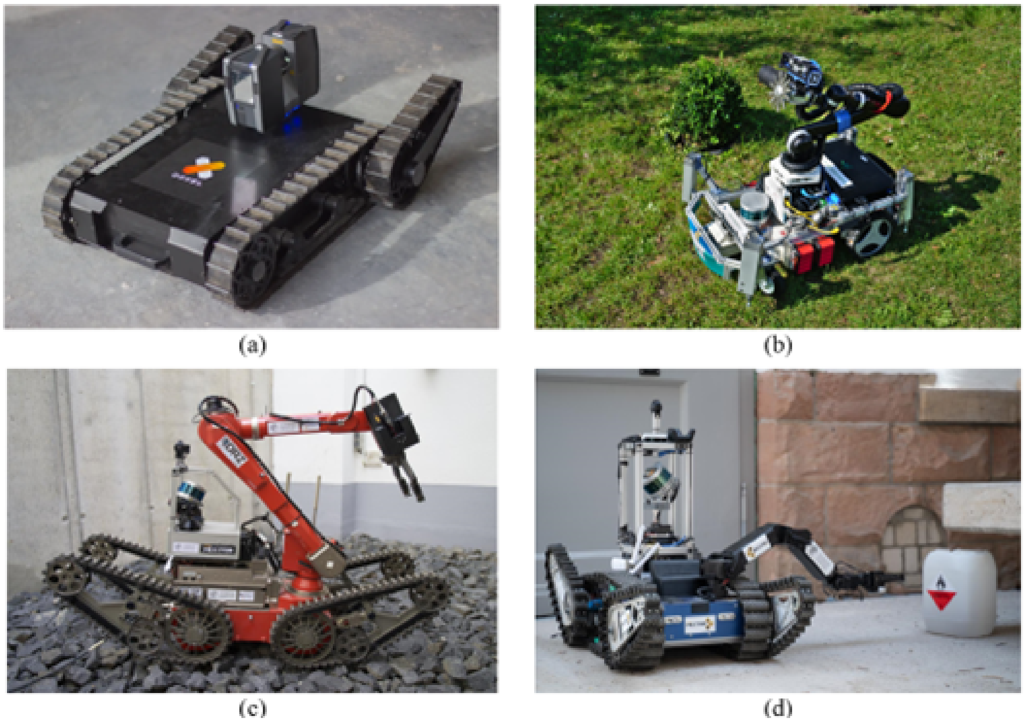
(a) (b) (c) (d)

Fig. 4 (a) Doxel's Robot [34]. (b) TrimBot2020 Robot [35]. (c) Hector DRZ Telemax [36]. (d) Hector Asterix [36].

Conclusions

This study offers a thorough review of recent advancements in robotic design across various fields, emphasizing the latest developments in automating welding tasks and innovations in robotic welding. It also examines progress in sensor technologies, such as enhanced vision systems, localization techniques, and tactile sensors. These advancements have greatly enhanced robots' ability to perceive and interact with their environments, enabling precise navigation, accurate task execution, and improving reliability in autonomous welding operations. Furthermore, this review explores mobility techniques tailored to welding robots, focusing on wall-climbing methodologies and related innovations. Wheeled robots utilizing magnetic and electromagnetic systems have emerged as suitable approaches for welding tasks, offering the necessary stability and maneuverability on vertical surfaces, although they may face challenges when crossing beam intersections. However, with the continuous advancements in robotic technology and design, it is expected that the complexities of beam intersections will be effectively addressed in future iterations, enhancing both the adaptability and efficiency of robotic welding solutions.

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