

Current Research Status of Climbing Operation Robots for High-Altitude Welding of Steel Structures

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Abstract

At present, research on high-altitude welding robots remains relatively limited. In outdoor environments, welding operations in areas such as steel structures and high-rise construction are typically performed manually. This practice poses significant risks to workers' personal safety. To address this design gap, one promising approach is to integrate climbing robots with welding robots. Accordingly, this paper reviews the current state of development of climbing robots from a design perspective and discusses key design considerations for equipping climbing robots with welding modules.

Keywords

Climbing Robots; Expanded Applications; High-Altitude Welding; Functional and Structural Design.

1. Introduction

Welding technology constitutes an indispensable technological component in modern industry, encompassing a broad range of sectors such as petroleum and petrochemical engineering, offshore construction, and vehicle manufacturing, and has even extended into microscopic domains [1][2]. In parallel with the expansion of its application scope, the operational environments for welding have continued to diversify; practical demands and theoretical innovations exhibit a mutually reinforcing and co-evolutionary relationship. Consequently, it is necessary to investigate welding under non-conventional conditions, including space environments, highly corrosive settings, and underwater environments[3]. In general, current research on welding technology may be broadly categorized into three directions. The first focuses on the intrinsic physical characteristics of welding, for example, analyzing the properties of the two major classes of techniques—fusion welding and solid-state welding [4]. The second centers on the welding carrier or platform, such as the design of welding robots or automated welding machines [5]. The third applies intelligent technologies or advanced algorithms to analyze welding applications, for instance, conducting artificial-intelligence-integrated analyses of solid-state welding technologies [6].

With the advancement of intelligent technologies, the automation and intelligentization of welding has become a major research direction, encompassing multifaceted developments [7], including automated welding equipment, welding robots, intelligent control of welding trajectories, and intelligent recognition of weld beads. This progression has, in turn, promoted the deployment of welding technologies across a wide range of application scenarios.

Steel structures refer to steel beams, columns, trusses, and related components fabricated from sections and steel plates, and they are extensively employed in contexts such as railways, bridges, oilfields, and residential construction, serving as a critical support system in modern architecture. Meanwhile, welding technology is widely utilized in the construction, installation, reinforcement, and retrofitting of steel structures, which often entails the challenge of high-altitude welding; the advancement of robotic technologies offers a novel approach to addressing associated safety concerns.

Considering the problem of welding on climbable steel structures, the robot must be able to traverse the steel framework and, upon reaching designated locations, perform welding operations. This process involves two critical subsystems: a steel-structure climbing mechanism and a welding mechanism. The design of a robot intended for steel-structure welding therefore requires an integrated consideration of the climbing mechanism's functionality and its compatibility with the welding subsystem.

2. Current Research Status of Climbing Robots Section Headings

2.1. Definitions and Classification of Climbing Robot

Research on climbing robots is relatively extensive. In general, any robot capable of achieving anti-gravity locomotion on the surfaces of vertical structures by means of a climbing mechanism may be regarded as a climbing robot. A wide range of classification schemes has been proposed; for instance, from an application-oriented perspective, climbing robots can be categorized into pole-climbing robots, pipeline-climbing robots, tree-climbing robots, wall-climbing robots, and other types.

Some studies have summarized tower-climbing robots according to their adhesion modalities into four categories: negative-pressure adhesion, electromagnetic adhesion, biomimetic adhesion, and mechanical clamping[8]. Such a classification scheme, which treats a specific technique as an independent category, is more appropriate for discussing research oriented toward the corresponding type of climbing application.

At present, the predominant climbing modalities can be broadly classified into two major categories: clamping-based and adhesion-based approaches. Clamping-based strategies can be further divided into three principal types: gripper clamping, hugging clamping, and ring clamping. Gripper clamping achieves secure attachment through grasping, hugging clamping provides fixation via compressive squeezing, and ring clamping realizes fastening by contracting a mechanism that encircles the entire climbing object. Adhesion-based strategies encompass a variety of implementations, including negative-pressure (vacuum) adhesion, electromagnetic adhesion, biomimetic adhesion, and thrust-assisted adhesion. Current research on adhesion-based methods is primarily focused on the optimization and iterative improvement of adhesion mechanisms.

Locomotion modalities can be classified as rope-driven, wheeled, tracked, legged, biomimetic, and hybrid[9]. In addition, motorized peristaltic motion, soft-bodied structures[10], and propeller-based propulsion[11], should also be considered. The purpose of locomotion design is to enable anti-gravity movement of the robot. A wide range of mechanisms can achieve this objective; however, the key consideration lies in their compatibility with the selected climbing modality and the functional modules.

Different climbing modalities exhibit varying degrees of compatibility with different locomotion modalities, and certain pairings are relatively more suitable and mature—for example, hugging clamping with motorized peristaltic motion, and biomimetic adhesion with biomimetic locomotion.

In summary, the functional architecture of a climbing robot comprises two principal categories of mechanisms: climbing and locomotion. Therefore, a more rational classification scheme would treat the climbing modality as the primary level of classification and its implementation strategy as the secondary level. Meanwhile, locomotion modality can be regarded as an independent classification dimension, as shown in Table 1.

Table 1. Classification of Climbing Robots

Primary Category	Secondary Category	Locomotion Modality
Clamping-based	Claw clamping	Biomimetic locomotion
	Hugging clamping	Wheeled
	Ring clamping	Hybrid
Adhesion-based	Negative-pressure adhesion	Tracked
	Electromagnetic adhesion	Propeller-based
	Biomimetic adhesion	Motor-driven peristaltic motion
	Thrust-induced adhesion	Legged
Traction-based	Rope traction	Rope-driven

2.2. Current Research Status of Climbing Robots

Research on climbing robots can be broadly categorised into three major classes. The first focuses on innovations in mechanical architecture to accommodate or enable operation across diverse working environments. The second emphasises the extension and evolutionary refinement of functional mechanisms to achieve improved locomotion performance. The third concentrates on iterative advances in motion and control strategies, aiming to develop more robust and higher-precision control schemes.

Given that climbing robots designed for welding on steel structures essentially integrate a climbing mechanism with a welding module, the present discussion primarily addresses the mechanical structures of climbing robots.

2.2.1. Clamping-Type

Research on this category is relatively extensive. Its design relies on mechanical structures that envelop the climbing substrate to achieve fastening. Clamping strategies for this type of robot include gripper clamping, embracing clamping, and ring clamping. The principal advantage of this approach is its adaptability to more complex climbing substrates, without requiring planar surfaces or specific material properties. However, its limitations include the need to address locomotion stability and balance, while imposing more stringent requirements on the robot’s motion reliability.

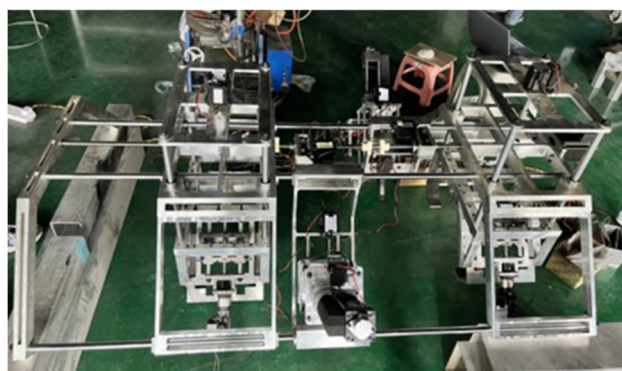


Figure 1. Embracing-clamp climbing robot

Xue Min developed a fastening robot suitable for angle-steel tower structures[12]. The clamping strategy adopts an embracing clamp, and the locomotion strategy employs motor-driven inchworm motion. By emulating the roles of human hands and feet during climbing, a bipedal climbing mechanism was designed, with locomotion realized via a lead-screw motor. The specific structure is shown in Figure 1. In addition, the robot’s ventral–dorsal section is

hollowed out, and the working module is mounted laterally. During movement, the robot remains parallel to one side surface of the angle steel, thereby alleviating constraints on payload space while enabling effective bolt fastening. In this design, the gripper mechanism conforms to the geometric surface of the angle steel; for climbing substrates with other geometries, the mechanism can be redesigned according to the corresponding requirements.

Yue Wei developed a three-claw climbing robot[13]; its clamping strategy employs claw-type gripping, and its locomotion adopts a biomimetic inchworm-like gait. Owing to its simple structure, surplus space is available on the ventral, dorsal, and lateral sides during locomotion, providing favorable conditions for subsequent integration of functional modules.

Kou Yongsheng designed a climbing robot for angle-steel structural members[14]; it likewise uses claw-type gripping and an inchworm-like locomotion strategy, as shown in Figure 2. The design is compact with a small footprint, enabling it to climb angle-steel tower structures, traverse obstacles such as step bolts and crossbars, and provide a certain degree of steering capability. This configuration can achieve relatively high mobility. Lin T. H. et al. applied an inchworm climbing robot to steel bridge inspection, where its high mobility enabled effective inspection on complex surfaces[15]. In such designs, a key mechanism is the central rotary joint that facilitates contraction and extension of the front and rear units. With respect to payload accommodation, a dedicated working platform may be considered to support operational mechanisms, thereby meeting the intended design requirements.

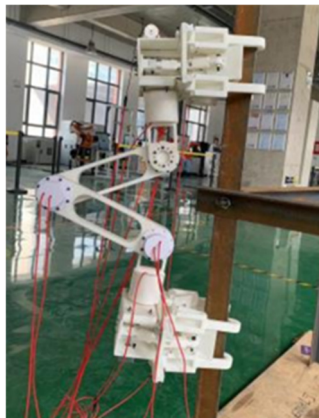


Figure 2. Dual-claw climbing robot

As shown in Figure 3, Liu Xue developed a ring-type heavy-load climbing robot[16]; its clamping strategy adopts a ring clamp, and its locomotion is based on motor-driven inchworm motion. The robot consists of two semicircular structures (upper and lower bodies) that can open and close. During installation, the two semicircles are opened to enclose the target wooden utility pole or standing tree, and are then closed and secured to form a complete circular ring that wraps around the climbing object. Anti-gravity locomotion is achieved via worm-like extension and contraction of the connecting body, which is realized by push rods driven by independent motors, providing a load capacity of up to 1500 N. This design is advantageous for addressing heavy-load requirements, enabling the robot to support heavy-duty operational modules and move against gravity to a designated position.

Jang K. et al. also employed a ring-type climbing robot for evaluating cracks in high bridge piers[17]; the robot conforms to the climbing substrate and can complete inspection tasks through effective locomotion. Because ring-type climbing robots must encircle the climbing object, their motion is confined to a limited region on the surface of the substrate; consequently, obstacle-surmounting capability is restricted, and such robots are applicable primarily to columnar climbing objects whose surface obstacles fall within allowable height limits.



Figure 3. Ring-clamp climbing robot

2.2.2. Adhesion-Type

Adhesion-type climbing robots refer to systems that establish attachment to a substrate surface via adhesion forces generated by the climbing mechanism, thereby enabling locomotion against gravity. Their adhesion modalities include negative-pressure suction, magnetic adhesion, adhesives, mechanical interlocking, and hybrid adhesion. The primary advantage of this approach is that it can provide a stable attachment interface during climbing. However, it imposes certain requirements on surface planarity and must additionally ensure adequate sealing performance after the adhesion material interfaces with the substrate.

Li Xiang developed a negative-pressure suction robot for wind turbine blades[18]; the adhesion method is negative-pressure suction, and locomotion is realized via legged movement. Double-layer bellows-type vacuum suction cups are mounted at the foot ends. The suction cups are connected via pneumatic tubing to an air-control adhesion circuit comprising a vacuum pump, solenoid valve, check valve, and pressure sensor. By generating a low-pressure environment inside the suction cups, the robot adheres to the blade surface. In this design, the spatial relationship between the robot body and the substrate surface can be adjusted through the corresponding mechanical structure (e.g., the leg mechanism), thereby enabling different directional operation requirements under varying task configurations.

As shown in Figure 4, Yang Zikang designed a biomimetic soft climbing robot; the adhesion strategy is negative-pressure suction, and locomotion mimics the caterpillar-like gait of *Eudocima* larvae[19]. The suction cups are fabricated from silicone, and anchoring and release are achieved by controlling inflation and deflation. This design is compact and readily controllable; however, its load capacity is limited.



Figure 4. Negative-pressure suction robot

As shown in Figure 5, M. Gao designed a multi-link, magnetic-wheel pipeline robot. Its adhesion method falls under magnetic (electromagnetic) adhesion, and its locomotion mode is wheeled[20]. The magnetic wheels use rectangular NdFeB (neodymium-iron-boron) permanent magnets. The driving wheels at the head and tail adopt a double-row magnet

arrangement to enhance and maintain adhesion stability while climbing along the pipe wall, whereas the intermediate idler wheels use a single-row magnet arrangement to reduce overall weight. Obstacle-surmounting is achieved by adjusting the angles of the head, middle, and tail sections via a pitch joint. The overall structure resembles train cars connected in series, which facilitates the modular, serial integration of multiple functional modules.



Figure 5. Magnetic-adhesion robot

Jiang et al. designed a passively adaptive locomotion mechanism for a wheel-based adhesion climbing robot[21]. This mechanism employs a dual-hinge connection architecture and a clearance-type permanent-magnet adhesion device to achieve passive adaptive motion on metallic façades with varying curvature. The proposed design enables posture regulation and obstacle negotiation without active control, featuring a concise and robust structure, and thus provides an extensible concept for the development of related robotic platforms.

Fang Shengchang developed a biomimetic quadrupedal climbing robot inspired by insect tarsal morphology[22]. The adhesion strategy is biomimetic adhesion, and the locomotion mode is legged locomotion. During climbing, an underactuated claw–spine footpad serves as the contact interface; the claw spines mechanically interlock with rough wall surfaces to generate the attachment force required for locomotion. The main body of biomimetic climbing robots is typically in contact with the climbing surface or maintains a minimal standoff distance. If the payload is to be extended to accommodate various functional modules, positioning these modules on the lateral and dorsal sides is the preferred solution.

Satyendra et al. proposed a lizard-inspired robot that achieves attachment and detachment using pressure-sensitive adhesive (PSA) pads[23]. As illustrated in Figure 6, the fundamental principle leverages the PSA characteristic that “edge or corner peeling is facile, whereas central peeling is difficult.” Reliable adhesion is realized via compliant finger-like structures under spring preload, while a servo-driven cable enables controlled edge peeling, thereby facilitating stable climbing. The average vertical climbing speed was reported as 1.35 cm/s under no load and 1.25 cm/s when carrying a 20 g payload. Because the PSA pads occupy minimal space, the overall size of this class of robots is primarily determined by the robot body. This design is conducive to the miniaturization of climbing robots and provides favorable support for applications involving lightweight functional modules, such as inspection and information acquisition.

Another design paradigm employs thrust generated by propellers to drive the entire robot, thereby enabling adhesion and locomotion on vertical walls. Robots of this type can be categorized into non-flying and flying configurations. Mahmood S. K. et al. developed a wall-climbing robot based on a propeller-thrust adhesion mechanism that can operate on various surface types[24]. This robot is non-flying and features two terrestrial locomotion modes as

well as two ground-to-wall transition strategies: one achieves rapid transitions using an L-shaped telescopic arm, whereas the other, inspired by kangaroo standing behavior, elevates the robot's front end via a manipulator to shift the center of mass forward, thereby realizing posture transition without wall contact under the action of gravitational torque.

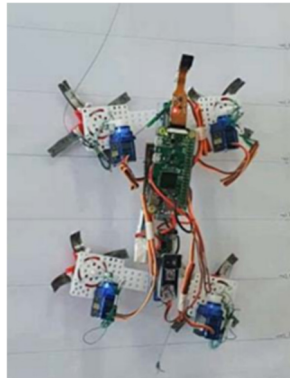


Figure 6. Lizard-inspired climbing robot

As shown in Figure 7, Myeong W. et al. proposed a flying propeller-driven climbing robot[25]. The system is built on an X-configuration quadrotor UAV platform, with front and rear thrusters mounted on tiltable arms. Two actuators drive synchronous tilting with a range up to 180° . In addition, the robot is capable of vertical soft landing, which mitigates the impact risk induced by rapid attitude changes in conventional approaches and improves adaptability to complex surfaces. Unlike traditional adhesion concepts that primarily rely on foot-end structures, this class of robots integrates UAV design principles to transcend conventional paradigms and provides a novel solution for carrying functional payload modules.

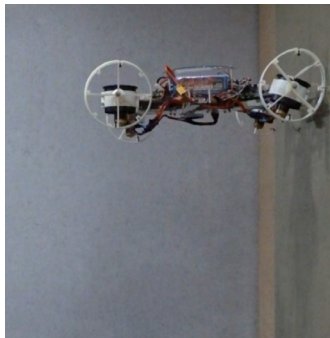


Figure 7. Propeller-driven climbing robot

2.2.3. Traction-Driven Type

Traction-driven climbing robots are characterized by the installation of a fixed ascender at the top of the climbing route, which drives the robot to move against gravity via tensile pulling.

Tang Chaoquan et al. developed a wheeled climbing robot based on the lay direction of wire ropes[26]. As shown in Figure 8, the robot fulfills task requirements along a prescribed trajectory through wire-rope traction. Kim et al. proposed a rope-driven climbing robot. The rope ascender mounted on the top of the platform drives vertical ascent and descent along the wall by winding or releasing the rope[27]. The rope is anchored at the top of the building, while the platform stabilizes and grips the rope through its own weight and a V-shaped pulley mechanism. By controlling the forward and reverse rotation of the ascender motor, the platform can perform upward and downward motions. Industrial fans or vacuum suction cups are employed to provide adhesion, ensuring close contact with the wall surface and preventing detachment. Certain variants are additionally equipped with wheels as buffering components

to mitigate severe impacts with the wall. The primary advantages of this design include compactness, lightweight structure, relatively low implementation cost, and highly controllable motion trajectories. However, its limitations lie in the requirement to anchor the rope at the top of the building, which constrains deployment in some scenarios, and in the need for additional preparation of fixed anchoring points prior to installation for traction.



Figure 8. Rope-driven climbing robot

3. Extended Welding Applications of Climbing Robots

To accommodate diverse vertical structures, climbing robots are required to satisfy several design criteria, including flexibility, payload capacity, functionality and tool-carrying capability, as well as additional factors[28]. When extending the functionality of a climbing robot, it is necessary to jointly consider both the inherent design requirements of the climbing robot and the design requirements imposed by the added functions.

3.1. Design Considerations for Welding

At present, in non-welding domains, climbing robots have been extended to a variety of applications, primarily in two aspects: operational manipulation and information acquisition. Li Xingxing addressed the problem of coconut harvesting by developing a climbing coconut-picking robot[29]. The design adopts a ring-clamping configuration, with the cutting module positioned on the upper part of the supporting ring, thereby matching the operational conditions and enabling efficient coconut harvesting. Fu Min et al. proposed a concept in which a detection module is integrated into a clamping-type climbing robot, allowing the robot to identify pest infestations in Korean pine[30].

Similarly, the extension of welding capability must be aligned with the task objectives. Current welding robot designs can be broadly categorized into large-scale and small-scale systems. Large-scale welding robots typically rely on fixed sites and are implemented as integrated workstations, such as the gantry-type robotic welding workstation designed by Yan Ming and the all-position pipeline welding robot developed by Feng Chuanzhi[31][32]. In contrast, small-scale welding robots are designed for specific operational environments. As shown in Figure 9, Song Jiangyi developed a compact mobile welding robot that connects a welding manipulator to a four-wheel chassis to meet welding demands in complex environments[33]. Huang Chao proposed a compact in-pipe welding robot capable of autonomous locomotion within pipelines, making it suitable for construction scenarios with severe spatial constraints[34].

The welding module can be decomposed into three components: a wire-feeding unit, a motion actuation unit, and a welding end-effector. Under elevated and high-altitude operating conditions, the welding module must ensure stable performance, which imposes requirements on both the mechanical architecture and the control system. From a mechanical perspective,

welding demands high end-effector pose stability and trajectory continuity. There exists a coupled relationship among torch orientation, torch-to-workpiece standoff distance, welding speed, and wire-feeding speed. Any end-effector vibration or variation in relative distance can readily induce defects such as non-uniform bead formation, undercutting, and lack of fusion. Therefore, the welding module design should account for center-of-mass distribution, vibration resistance, protective measures and thermal management, as well as cable and gas-line routing and organization.



Figure 9. Compact mobile welding robot

3.2. Design Issues Under Different Climbing Modes

Different types of climbing robots impose different requirements on the surface of the climbing object. Taking steel structures as an example, the design issues can be discussed as follows.

3.2.1. Clamping-Type Climbing Robots

Clamping-type robots achieve attachment by gripping component edges, flanges, or the flanges of structural steel sections. Their main advantage is low sensitivity to surface roughness and contamination, leading to relatively high attachment reliability; they are therefore suitable for steel members with coatings, corrosion, or local unevenness. During welding, the clamping mechanism is subjected to dynamic loads and impacts. In practice, steel sections vary significantly, so the clamping system must provide an adequate adaptation range or use replaceable jaws to ensure stable gripping across different cross-sections. Because the clamping unit typically occupies edge space, it may conflict with the torch motion envelope, requiring coordinated mechanical layout between clamping locations and the welding workspace. If the clamping region is close to the weld zone, thermal conduction can degrade jaw material performance; additionally, the conductive path through the metal structure should be electrically isolated to reduce leakage current and mitigate electromagnetic interference risks.

Accordingly, design should consider: clamping force and safety margin, cross-section adaptability, welding reachability, thermal effects and insulation.

3.2.2. Adhesion-Type Climbing Robots

Adhesion-type robots offer flexible mobility and can move easily over planar or large curved surfaces, making them suitable for large-area steel plate structures such as ship hulls and storage tanks. The contact footprint of the adhesion module must be smaller than the available usable surface width to avoid insufficient adhesion area near narrow flanges, edges/corners, or stiffeners. Increasing the number of adhesion units raises size and mass, which can degrade mobility; thus, a balance is required together with anti-fall redundancy measures. Negative-pressure adhesion is sensitive to surface flatness and sealing quality. Welding current and arc-generated magnetic fields may affect electromagnetic adhesion performance and sensor signals,

so electromagnetic compatibility (EMC) should be addressed, with appropriate measures in power distribution, grounding, and shielding.

Accordingly, design should consider: adhesion-module size constraints, payload and anti-tip stability, sensitivity to surface condition, arc interference and safety.

3.2.3. Traction-Driven Type Climbing Robots

Traction-driven robots rely on external anchor points, guide rails, or traction devices to move along predefined paths. Their advantages include high payload capacity, high positioning accuracy, and strong system stability, making them suitable for long weld seams, repeated trajectories, or high-risk environments. Key challenges include anchor location selection, installation methods, and load verification—especially for high-altitude steel structures where anchor accessibility and installation cost must be evaluated. Rails or ropes define the reachable workspace, making them appropriate for welding tasks with clear paths. However, ropes can couple with welding cables and induce swing, amplifying end-effector disturbances; swing effects should be mitigated via tension control or related strategies. Finally, the coordination between the fixed infrastructure and the robot body requires an overall integration plan; otherwise, practical applicability can be reduced.

Accordingly, design should consider: traction and anchor layout, operational coverage, cable management and swing suppression, system integration.

4. Conclusion and Outlook

Overall, the climbing and locomotion modalities of climbing robots have reached a relatively mature stage, while still presenting substantial room for innovation. The complexity of real-world scenarios requires that robot design no longer remain confined to a single discipline, but instead evolve toward interdisciplinary and cross-domain integration.

In recent years, the rapid advancement of artificial intelligence has opened new avenues for both welding and robotics. Within this context, welding robots can be more effectively extended to operate in increasingly complex environments. At present, research on robots for outdoor high-altitude welding remains limited; integrating climbing robots with welding technologies can provide an effective means of addressing this need. Future developments are expected to build on this foundation, advancing toward higher levels of safety, stability, and intelligence.

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