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A Survey of Climbing Robots: Locomotion and Adhesion

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Climbing robots are robotic systems to move over 2D or complex 3D environments such as walls, ceilings, roofs, and geometric structures and to conduct various tasks. They will not only replace human workers for carrying out risky tasks in hazardous environments, but also increase operational efficiency by eliminating the costly erection of scaffolding and staffing costs. Climbing robots have special characteristics and the ability to adhere to different types of 2D or 3D surfaces, move around, and carry appropriate tools and sensors to work, while self-sustaining their bodies. Therefore, the most significant criterion for designing a climbing robot is to equip it with an appropriate locomotive and adhesion mechanism for adapting to the given environmental requirements. In this paper, a classification of climbing robots and proper examples with a brief outline are presented with considerations of the locomotive and adhesion mechanisms. Also, a list of climbing robots is provided with respect to fields of application that range from cleaning tasks in the construction industry to human care systems in the biomedical service industry.

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1. Introduction

Being a special kind of mobile robot, climbing robots are robotic systems for moving over 2D or complex 3D environments such as walls, ceilings, roofs, and geometric structures and for conducting various tasks. Climbing robots have been a very attractive research topic since there are a great number of potential applications that cannot be performed directly by human operators because of difficulties in accessing the operating positions in a proper and safe manner. Therefore, climbing robots can be great alternatives that increase operational efficiency and protect human health and safety from hazardous tasks such as the following: cleaning and inspection of high-rise buildings, evaluation and diagnosis of storage tanks in nuclear power plants and petrochemical facilities, welding and maintenance of ship hulls, and so on.[1]

Other than mobile robots that move on the ground with wheels or legs, climbing robots possess the unique characteristic of sustaining their bodies against gravity while moving in 3D environments.[2] As such, the following requirements should be observed to design climbing robots.[3]

- Lightness of weight, which is followed by low energy consumption, to increase the autonomy and payload of the auxiliary equipment.
- High mobility, which enables the climbing robots to move over various environments with different geometries and materials such as bricks, glass, cement, steel, and so on.
- A reliable grasping mechanism for climbing on various surface types.

As such, robot designers must consider not only locomotive, as in all mobile robot systems, but also adhesion aspects, which are the two major issues in the design of climbing robots. Over the last few decades, a great number of studies have been devoted to climbing robots, and various types of experimental prototypes and products have been proposed. With respect to the locomotive mechanism, climbing robots can be divided into six categories: legged type,[3-52] wheel-driven type,[53-70] tracked type,[71-80] translation type,[81-96] cable-driven type,[97-104] and combined type.[105-111] On the other hand, from the adhesion point of view, climbing robots can be classified into five categories: suction type,[3,6,8-10,12,14,19,22,23,35,37,40,47,50,53,57,58,60,61,63,68,69,74-76,81-85,88,92,94-96,98-100,102,103,107,110] magnetic type,[24,51,59,61,62,65-67,72,73,78,80,86,112] gripping type,[3-5,7,9,11,13,15-18,20,21,25-27,29-31,41-43] rail-guided type,[87,89,91,93,101,103] and biomimetic type.[32,34,36,38,39,44-46,48,49,52,54-56,64,70,79,113,114] Further, different adhesion and locomotive mechanisms can be combined to form various climbing robots.

The paper is organized as follows. Section 2 deals with the locomotive mechanisms of various climbing robots. In Section 3, the climbing robots are rearranged with regard to the adhesion mechanism. Section 4 presents a complete list of climbing robots with respect to application fields that range from cleaning tasks in the construction industry to human care systems in the biomedical service industry. Finally, in Section 5, concluding remarks are addressed.

2. Locomotive Mechanism of Climbing Robots

2.1 Legged Locomotion

A number of different kinds of mechanisms for locomotion on 2D surfaces or 3D structures have been presented over the past decades. A representative method for implementing locomotion is the adoption of legs.[3-52] Climbing robots that employ legged locomotion have from two up to eight legs that are equipped with vacuum suction cups, grasping grippers, or magnetic devices at the end of the feet. These devices for attachment enable strong and stable adhesion to the surface. Since they usually have a lot of degrees of freedom, they can move over rough surfaces and cracks, and are capable of good obstacle avoidance. However, they require complicated control systems because of the use of harmonic gait control and have the disadvantage of low speeds of motion due to discontinuous movement.[100]

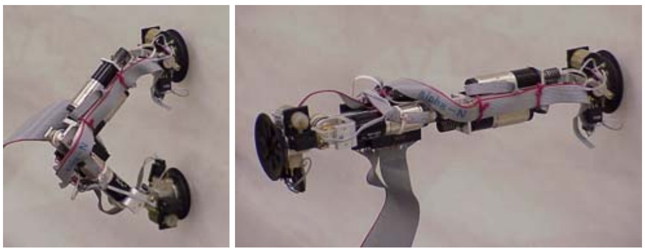
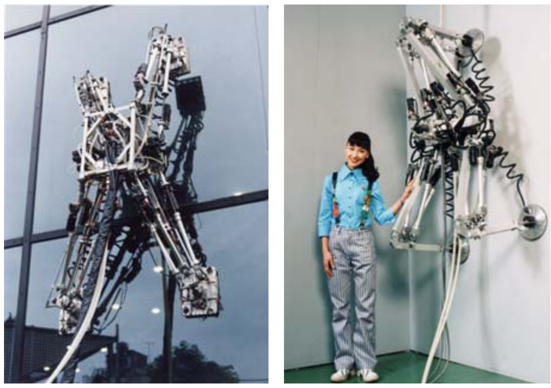


Fig. 1 RAMR 1 walking (climbing) on a surface[14]

A greater number of legs of a climbing robot lead to a greater supporting force in the environment, which increases the capacity in terms of the payload and safety.[14] However, an increase in the number of legs also increases the control complexity and the size and weight of the robot at the same time. Therefore, climbing robot systems that require a compact size and high energy efficiency adopt a biped structure.[3-31] RAMR 1 is a biped robot with four joints, five links, and a suction adhesion mechanism at the ends of its legs (Fig. 1).[14] It employs an under-actuated structure that contributes to weight reduction and space savings by coupling the rotation of the hip joint and one ankle joint to allow three motors to drive four joints. Thus, the prototype measures approximately $45x45x248mm^3$ and weighs 335g.

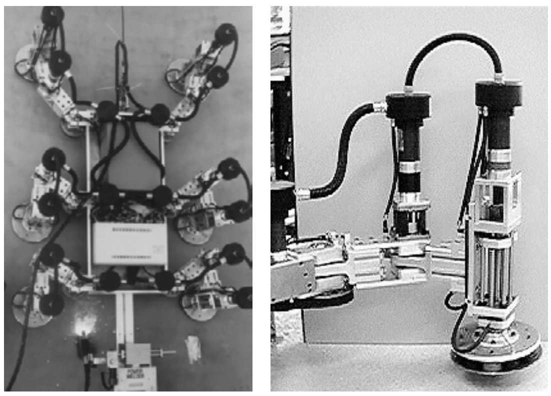
When increased safety or larger payload capacity is required, quadruped climbing robots are adopted.[32-45] Fig. 2 shows quadruped climbing robots, NINJA-I and NINJA-II, which the Tokyo Institute of Technology developed for the purpose of facade inspection and maintenance of high-rise buildings and bridges.[35,40] They are composed of 1) a 3D parallel link mechanism capable of producing the driving force for moving on a surface, 2) a conduit-wire-driven parallelogram mechanism to adjust the posture of the ankles and 3) a valve-regulated multiple sucker capable of sucking force even on uneven surfaces. However, while the thrust force along the vertical axis is 1400N, it has a size of $500x1800x400mm^3$, mass of 45kg, and maximum speed of 0.16m/sec.



(a) NINJA-I (b) NINJA-II

Fig. 2 Wall climbing robots, NINJA-I and NINJA-II[35,40]

With even greater size and weight, six- or eight-legged climbing robots have been developed to enable increased stability and payloads.[46-52] The REST 1 climbing robot, which has six reptile-type legs with 3 DOFs each, was originally proposed to perform inspection, cleaning, and welding tasks of a ship hull.[51] The leg kinematics are of the SCARA type. The feet at the ends of legs are furnished with electromagnetic grasping devices that secure the robot to ferromagnetic material walls (Fig. 3). Thus, the weight also increases up to 250kg and the robot entails high complexity for operating a master PC for managing slave processors that control 8 DOFs in real time. The trade-offs of the increased stability and payload are the increased size, complexity, and weight.

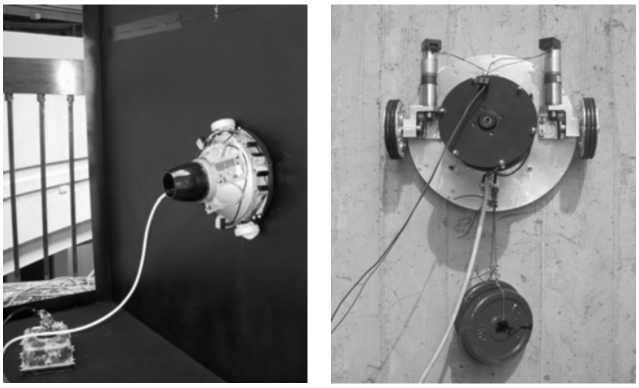


(a) REST 1 (b) Electromagnetic gripper

Fig. 3 REST 1 climbing robot welding a ship hull[51]

2.2 Wheel-Driven Locomotion

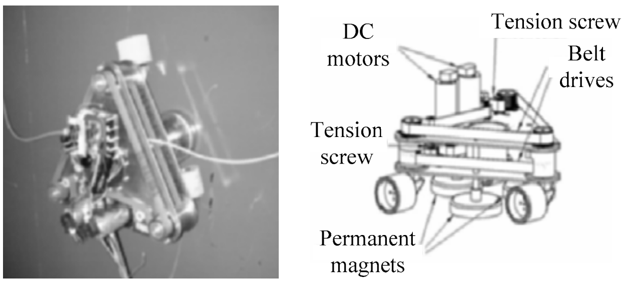
Wheel-driven climbing robots climb vertical planes and ceilings by combining wheels for translation and rotation and vacuum pumps or magnets for surface attachment.[53-70] Therefore, they move continuously and subsequently, their speed can be improved considerably. For using suctional force for attachment to the surface, some wheel-driven climbing robots have an air gap between the base and the surface to be driven over.[115] While this kind of system has to move over the target surface, which generally is a rough metal surface or concrete wall, the suctional device must not completely adhere with a high degree of friction; therefore, a particular kind of sealing is required between the wall and the robot. The sealing must guarantee negative internal pressure and should allow the robot to pass over small obstacles. Such robots cannot handle large obstacles and their payload capacity is small.



(a) Alicia 1 (b) Alicia 2

Fig. 4 The Alicia 1 and 2 prototypes[53]

The aim of Alicia 1 and 2 is to inspect non-porous vertical walls such as those in above-ground petrochemical tanks.[53] To keep the operation of the system independent of the surface material, they use two driving wheels, suction cups, and a vacuum generator (Fig. 4). They are designed to pass over small obstacles (about 1cm) at a normal velocity and bigger obstacles at a lower velocity. Since this kind of suction cup has unavoidable vacuum leakage, an air aspirator with very high air flow capacity and PVC cup with a large diameter for sealing are utilized. Alicia 2 has a diameter of 30cm and a payload of 10kg while it weights 4kg.



(a) Robot on a vertical surface (b) CAD model

Fig. 5 A three-wheeled synchro drive vehicle[66]

Meanwhile, a versatile lightweight climbing robot has been designed as a three-wheeled synchro drive vehicle (Fig. 5).[66] It is capable of moving on the hull of ships for tasks such as inspecting welding seams. The synchro drive mechanism allows movement in any direction without change in the orientation. While Alicia 1 and 2 use suctional force to adhere to the surface, the force of attraction that is necessary for the robot to stick to the ship's hull is provided by three permanent magnets that are placed at the bottom of the robot. A vision system using a multi-laser beam and a camera with an appropriate filter detect the groove that is formed by welding.

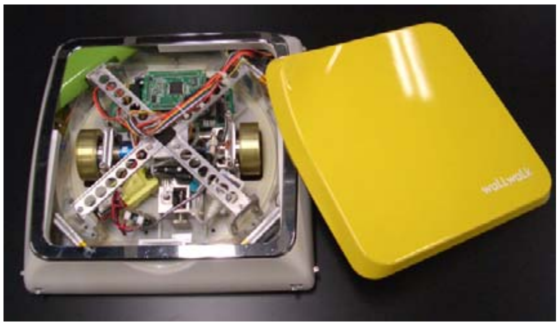


Fig. 6 WallWalker working on the window[69]

For a climbing robot using two independently driven wheels and a suction cup, WallWalker, a vacuum-based wet adhesion system has been adopted (Fig. 6).[69] With the ability to continuously change its traveling velocity, the robot can clean up all of the dirt on the window glass using the cleaning equipment that is installed in its body. Especially, it utilizes the sealing and lubrication actions of a liquid to be adherable and slidable on the surface.

2.3 Tracked Locomotion

Tracked climbing robots have a similarity to wheel-driven climbing robots in that both move with a rotational mechanism. However, using a chain-track as the locomotive mechanism, tracked climbing robots are better able to avoid obstacles and adhere to the surface.[71-80]

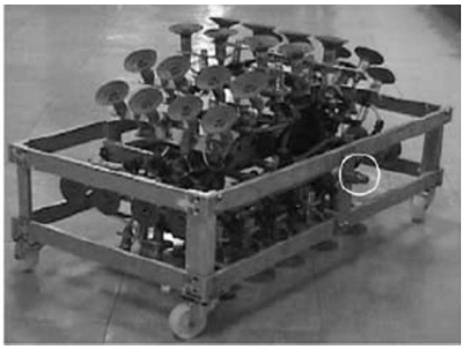
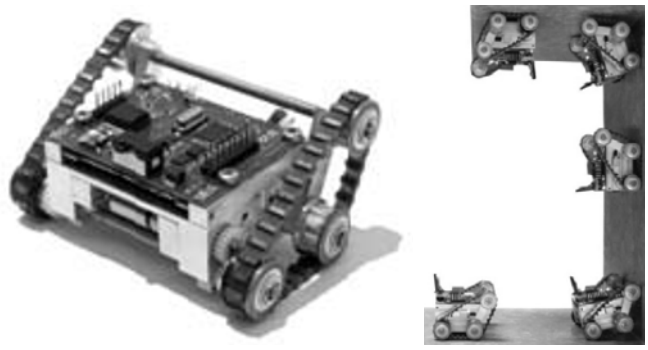


Fig. 7 The main structure of Cleanbot II[75]

Cleanbot II, which employs a chain track on which 52 suction cups are installed, can virtually achieve continuous movement (Fig. 7).[75] The vacuum suction cups are controlled by solenoid valves and supply adhesive force to make the robot stick to the glass surface. The robot can turn in a limited range by twisting the flexible chains and climb over an obstacle that is less than 6mm high. The maximum speed is 10m/min with a mass and payload of 22kg and 25 kg, respectively.

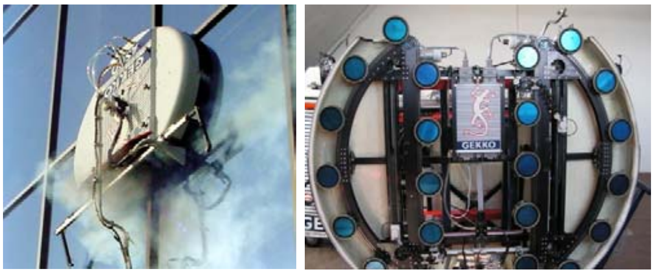
A miniature climbing robot of size 96x46x64mm^3 and named TRIPILLAR uses magnetic caterpillars in a triangular shape (Fig. 8).[80] The adhesive force is provided by a combination of small magnets that are molded in the caterpillars and magnets that are fixed to the robot's frame. Though its two triangular tracks can make only 2-DOF movements, TRIPILLAR can cruise on planar ferromagnetic surfaces at any inclination to gravity.



(a) TRIPILLAR (b) Climbing motion

Fig. 8 TRIPILLAR's movement from the floor to the ceiling[80]

Recently, a commercialized climbing robot, GEKKO III, has been developed by a German company, ARGECO.[74] It utilizes two planar tracks as the locomotive mechanism and a series of suction cups for attachment to glass walls, as shown in Fig. 9. It can clean glass surfaces and frames without leaving water stains and negotiate frames of up to 4cm thickness with a cleaning rate of up to 240m^2/h.



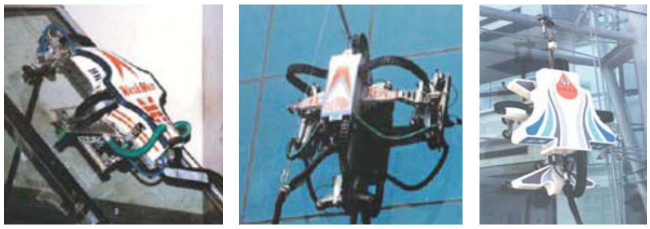
(a) GEKKO III (b) Planar track

Fig. 9 A commercialized climbing robot, GEKKO III[74]

2.4 Locomotion Based on Translation

One of the simplest ways for locomotion is to use a translational mechanism with an appropriate attachment device.[81-96] The control strategy and process to operate translational climbing robots are not complicated due to the easy movement that comprises of sticking-moving-sticking.[75] However, there are a few disadvantages such as the large size that hinders them from being used in a narrow space. Also, the movement is discontinuous and the speed is low.

Sky Cleaner 1, 2, and 3 are representative translational climbing robots.[83,90,92,94] These robots that are developed for glass-wall cleaning are actuated by pneumatic cylinders for translation; they are sucked to the glass wall through vacuum grippers (Fig. 10). Especially, Sky Cleaner 3 is a commercial product that is designed for cleaning the glass surfaces of the Shanghai Science and Technology Museum. It makes translational movements with two cross-connected XY cylinders and uses four short-stroke foot cylinders to lift or lower the vacuum suckers and support the body on the wall. While the robot is remotely operated to accomplish the glass-wall cleaning task, the system includes a support vehicle that is stationed on the ground and provides electricity, air, and cleaning liquid.



(a) Sky Cleaner 1 (b) Sky Cleaner 2 (c) Sky Cleaner 3

(d) Translation mechanism of Sky Cleaner 1, 2, and 3

Fig. 10 Sky Cleaner 1, 2, and 3 and the translation mechanism[83,90,92,94]

Recently, a climbing robot has been suggested for performing the grit blasting operation in shipyards.[86] The robot adopts a double sliding platform that uses permanent magnets for attachment (Fig. 11). The system is based on two modules that can move relatively to each other and can move up and along the shipside with any inclination during grit blasting. It can also rotate to compensate for the hull curvature and avoid obstacles while performing the grit blasting task.

Fig. 11 Grit blasting robot[86]

2.5 Cable-Driven Locomotion

Another alternative for the locomotive mechanism is to use a cable or tether.[97-104] A cable system that is equipped with a trolley on the roof of a building or structure can make vertical and horizontal movements and sustain the robot body at the same time.

A tether-supported climbing robot has been designed and realized for the purpose of glass-curtain wall-cleaning.[100,102] The robot does not have its own driving mechanism, but can move on smooth glass surfaces by depending on gravity and the lifting force of the trolley crane on the roof, while adhering to the surfaces using dual vacuum suction cups (Fig. 12). Obstacles such as horizontal window frames are detected by four groups of photo-electronic sensors and can be crossed while cleaning.

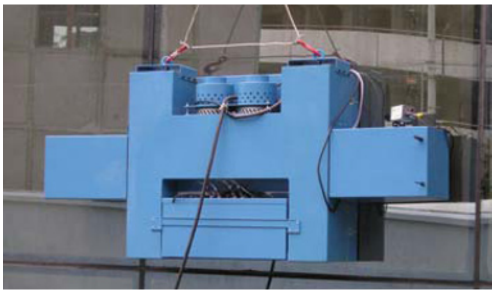


Fig. 12 Tether-supported climbing robot[100,102]

Actually, there have been a lot of commercial climbing robots in Japan that employ a cable-driven locomotive mechanism. Fig. 13 shows two examples of climbing robots for wall painting and wall inspection, which have been commercially developed by Taisei Corporation and Kajima Construction, respectively.[101] The robots are of a rectangular type and consist of a vertical carriage that is surmounted by an end-effector. The carriage moves up and down, covering vertical strips. Also, the carriage may be suspended from the roof or in some cases connected to a vertical 'mast' that is mounted on a mobile base. The end-effectors, which can be spray guns or inspection tools, can move on the carriage in the XY directions (in the plane of the carriage) or in the Z direction (perpendicular to it). Especially, the Taisei robot has been adapted for a particular type of high-rise building with an exterior wall containing decorative prefabricated panels.

(a) Taisei Corporation (b) Kajima Construction

Fig. 13 Cable-driven climbing robots[101]

2.6 Combined Locomotion

The final possibility for implementing locomotion is to combine the aforementioned locomotive mechanisms together to improve the climbing ability.[105-111]

An automatic facade cleaning robot, SIRIUSc, has been developed for use on a high-rise building.[107,111] The robot is supported by the cables of a gantry at the top of a facade, which lowers it down the side (Fig. 14). The gantry system with cables plays the role of moving SIRIUSc vertically and laterally from one panel of the facade to the next, which is the first locomotive mechanism. In addition, SIRIUSc is equipped with two pairs of linear translation modules, called an 'advanced sliding frame' mechanism. They ensure constant contact between the robot and the facade through the use of vacuum suckers and each module is driven to move the system both continuously and intermittently upward and downward in a relatively small range; this is the second locomotive mechanism.

(a) SIRIUSc (b) The gantry system

Fig. 14 A facade cleaning robot, SIRIUSc[107,111]

Alicia 3 is a newer version of Alicia 1 and 2 mentioned in Section 2.2 for improving the performance in passing over bigger obstacles.[110] Alicia 1 and 2 have one adhesion module with two driving wheels to maneuver over small obstacles under 1cm and climb walls with irregular surfaces. Alicia 3 links the three adhesion modules together by means of two rods and a special rotational joint, as shown in Fig. 15. As a result, this combined mechanism with both wheel-driven locomotion and legged locomotion enables the robot to move up and down to overcome obstacles of 10~12cm height in a few steps by detaching the three modules one by one, although it leads to a lower velocity. When the robot passes over obstacles, the two modules can support its entire weight; further, the two links between the three modules are actuated with two pneumatic pistons.

Fig. 15 Alicia 3 passing over obstacles[110]

3. Adhesion Mechanism of Climbing Robots

3.1 Adhesion Using Suction and Propulsion

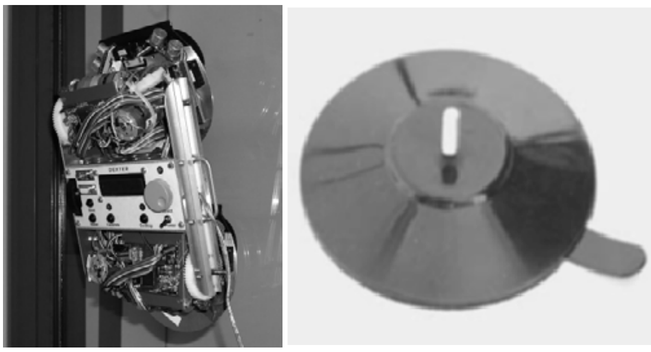
Vacuum suction, which is the most commonly used adhesion method, can be widely adopted for less rough surfaces because it enables strong attachment to the surfaces regardless of materials such as glass, ceramics tiles, and cement. The major disadvantage that is related to this adhesion mechanism is that any gap in the seal can cause the robot to drop. Therefore, this type is usually used in relatively smooth nonporous and non-cracked surfaces. Several researchers have attempted to overcome this problem.[3,6,8-10,12,14,19,22,23,35,37,40,47,50,53,57,58,60,61,63,68,69,74-76,81-85,88,92,94-96,98-100,102,103,107,110] The use of more than one suction cup, as in the tracked locomotive mechanism, may be a solution to prevent the loss of pressure and adhesive force due to surface irregularities.[75] The vacuum can be generated through the Ventri principle or a vacuum pump that is either on-board or external to the robot.

ROMA II is designed to inspect 3D complex environments with 4-DOF kinematics (Fig. 16).[3,9,10,116] In order to attain the mobility to visit all the faces of the metallic structures, ROMA II has two legs and a pneumatically driven grasping mechanism. The vacuum system that is adopted for this robot is able to produce a grasping force of 100kg that supports an overall weight of 20kg. Moreover, the grasping mechanism is formed by two platforms with ten vacuum cups, which are connected in pairs. In this way, even if one of vacuum cups does not work, there is only one pair that cannot stick to the surface. However, since the robot has limited mobility with only 4 DOFs, it takes a long time to change the working surface from one side to another side in 3D environments. The maximum speed of movement is at most 1.5m/min.

(a) ROMA II (b) Vacuum cups

Fig. 16 The ROMA II climbing robot[3,9,10,116]

Realizing climbing without a vacuum pump, the DEXTER climbing robot uses ‘passive suction’ to adhere to the surface (Fig. 17).[12,117] In general, suction cups are evacuated actively by at least one vacuum pump that is mounted on the robot. This is called ‘active suction.’ However, DEXTER uses ‘passive suction cups’ that are made of elastic material and are evacuated simply by pressing them to the surface. In this way, the vacuum is generated only by utilizing the robot’s locomotive system; no energy is consumed for adhesion. Then, the cups are normally released by pulling them away from the surface. While DEXTER has the advantage of compactness with a size of 36.5x22x13cm^3 and weight of about 3kg, even a very small gap between the passive suction cup and the surface causes the vacuum to break down in time, thereby requiring both flatness and cleanliness of the surface.



a) DEXTER (b) Passive suction cup

Fig. 17 DEXTER climbing a window[12,117]

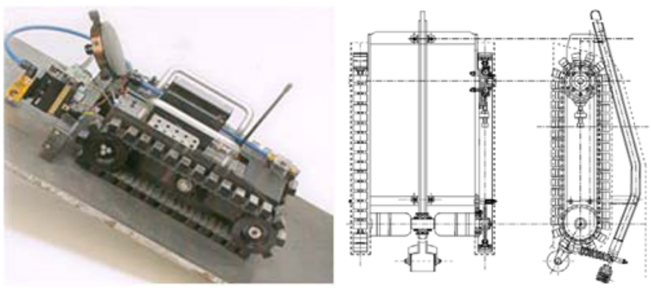
In an adhesion mechanism that uses propulsion, an airscrew is usually used to produce the thrust force and press the climbing robot on to the wall surface. To keep the propulsion-based wall cleaning robot, TITO, in a vertical position, a crane is used, which can move along the outer edge of the roof of buildings (Fig. 18).[98] A robot that hangs on a cable is a classic oscillatory system (pendulum). In order to overcome its lack of stability, the aforementioned climbing robot, SIRIUSc, has employed suction cups together with a sliding frame mechanism. However, instead of the complex structure and low velocity of SIRIUSc, TITO has adopted a powerful fan to create a grasping force for the surface and attained the ability to clean a facade of 10,000m^2 in just twelve hours.

(a) TITO (b) Industrial fan used to TITO

Fig. 18 The wall cleaning robot, TITO[98]

3.2 Magnetic Adhesion

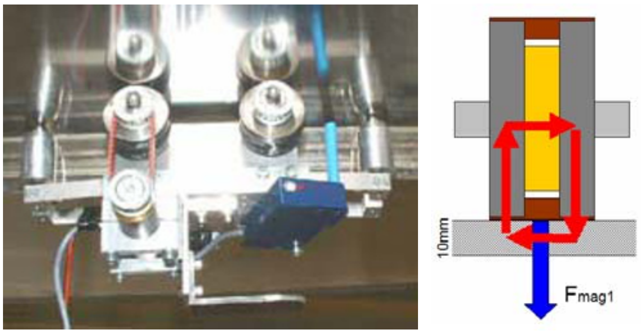
Magnetic adhesion solutions, including permanent magnetization or electrical magnetization, are suitable for attaching to only ferromagnetic surfaces though they are highly desirable due to their inherent reliability.[24,51,59,61,62,65-67,72,73,78,80,86,112] However, since a magnetic adhesion mechanism does not require time to generate a sufficient adhesive force, unlike suction-based adhesion, it enables fast locomotion. Especially, magnetic adhesion using permanent magnets has another advantage in that there is no need to spend energy for the adhesion process. Regarding applications, it can be applied at the ends of the legs of legged climbing robots or combined with wheels or tracks for moving along ferromagnetic surfaces.



(a) Entire body (b) Chain kinematics

Fig. 19 Wall climbing robot for inspecting oil tanks[78]

To carry NDT (non-destructive testing) tools for inspecting oil tanks, a wall-climbing robot has been developed.[78] A permanent magnetic adhesion mechanism and a tracked locomotive mechanism are chosen to attain high reliability, simple control, and high-speed operation. Each track is comprised of a roller chain, two sprockets, and some evenly arranged permanent magnetic units, as shown in Fig. 19. When the robot moves, there are always a certain number of units in good contact with the surface, which enables the robot to reliably stay on it, while carrying a payload of over 30kg.



(a) Climbing robot on magnetic wheels (b) Wheel structure

Fig. 20 Prototype of a mobile climbing robot[65,67]

The Swiss Federal Institute of Technology in Zurich has developed a mobile climbing robot on magnetic wheels for inspecting interior surfaces in gas tanks that are made out of thin metal sheets (Fig. 20).[65,67] The magnetic wheels are composed of a cylindrical magnet in the middle, two plates made of magnetic steel and of slightly larger diameter on either side, and a thin layer of rubber around the steel plates to increase the friction along the ground. Moreover, this robot uses four pairs of magnetic wheels that can be lifted with linear actuators in order to pass over obstacles on surfaces.

3.3 Adhesion Using Gripping Equipment

Gripping mechanisms for adhesion have been suggested to enable climbing robots to travel along 3D complex environments, while other adhesion mechanisms are usually applicable for climbing on flat walls and ceilings. Those gripping mechanisms are usually attached to parts of structures such as beams, columns, pipes, ducts, and even natural environments, through careful control of the grasping forces.[3-5,7,9,11,13,15-18,20,21,25-27,29-31,41-43]

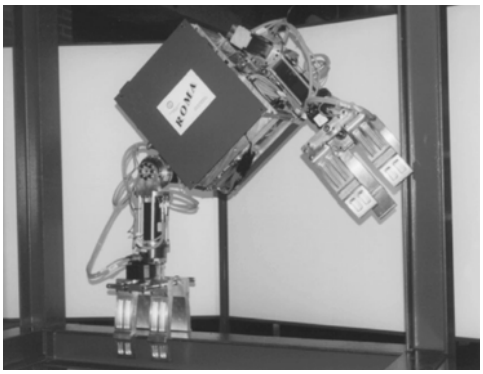
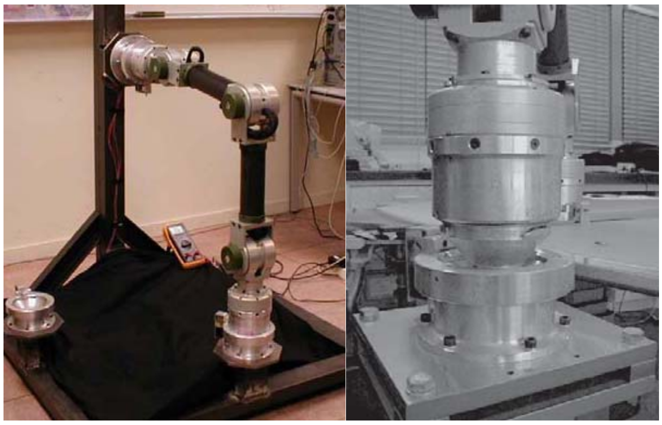


Fig. 21 The ROMA I climbing robot[3,9,10,116]

ROMA I is a multifunctional autonomous self-supporting climbing robot that can travel in a complex 3D metal-based environment that comprises of beams and columns.[3,4,116] ROMA I has two grippers to accomplish grasping tasks. The grippers encircle the beam to create a high degree of frictional force to avoid slippage and support the locomotive system for 3D movement, as shown in Fig. 21. In order to generate eight DOFs for 3D movement including two DOFs for grasping of the two grippers, ROMA I employs eight electric-motors, a power supply using on-board batteries, a metallic body, and complex kinematics. As such, it has a weight of 75kg; the locomotive speed for driving heavy systems is significantly limited to a maximum of 1m/min.

The EU (European Union) project, MATS, for flexible mechatronic assistive technology systems has developed a new concept of a climbing robot for the human-care service field.[7,9,10,15,20,21,30,31] The MATS robot can move from one room to another or from a static environment (walls, tables, etc.) to wheelchairs or vice versa by climbing (Fig. 22). It has a symmetrical 5-DOF system and a special gripping mechanism comprised of docking stations (DSs), which are placed in the environment and at the end of the climbing robot. The climbing process is performed by moving the robot between the DSs. It is lightweight (about 11kg) for a 1.3m reach and can conduct auxiliary tasks (eating, shaving, putting on make-up, etc.) for disabled people.

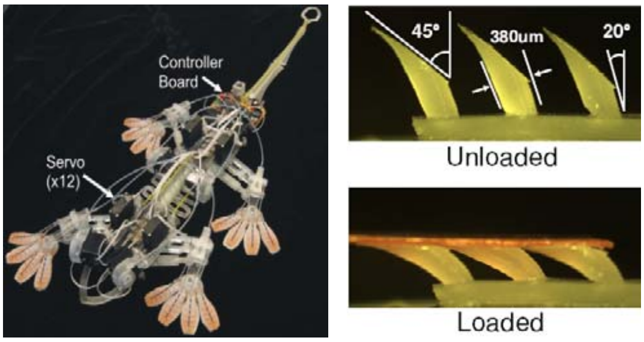


(a) The MATS robot (b) A docking station (DS)

Fig. 22 The MATS robot and docking stations (DSs)[7,9,10,15,20,21,30,31]

3.4 Biomimetic Adhesion

Recently, a great number of researchers have focused on the sticking ability of geckos. They adhere to surfaces using patches of microscopic hairs that provide a mechanism for dry adhesion through van der Waals forces.[64] Since the dry adhesion is mainly due to molecular forces, geckos have the ability to attach to almost any surface, whether wet or dry, smooth or rough. In the last decade, a group of climbing-robot researches have sought to employ biomimetic adhesion with nanofabrication techniques.[32,34,36,38,39,44-46,48,49,52,54-56,64,70,79,113,114] Similar to permanent magnetic adhesion mechanisms, climbing robots that use biomimetic adhesion do not need energy to stay on the surface or pressure differences to climb. However, they have a few disadvantages, such as a very low payload and sensitivity to surface conditions involving dust.



(a) Stickybot (b) Polymer stalks

Fig. 23 Stickybot, an experimental climbing robot[36,39,44,114]

Stickybot is a bio-inspired robot that climbs smooth vertical surfaces such as glass, plastic, and ceramic tiles at 4 cm/s.[36,39,44,114] Stickybot's toes are covered with arrays of small, inclined polymer stalks that induce adhesive forces with regard to the surface (Fig. 23). As with the directional adhesive structures used by geckos, the toes readily adhere when pulled tangentially from the tips toward the ankles and release when pulled in the opposite direction. However, the adhesive patches of the toes should be periodically cleaned to maintain adequate performance to allow Stickybot to continue climbing well after about three-to-four meters of climbing.

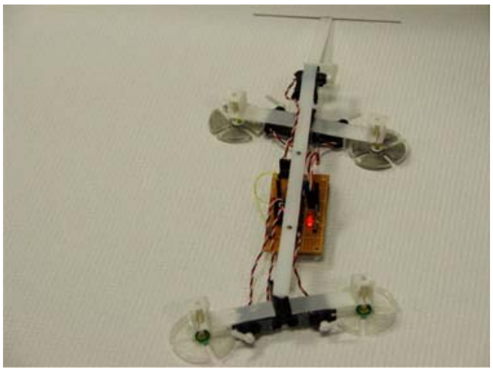


Fig. 24 A gecko-inspired climbing robot, Geckobot[38]

Another gecko-inspired climbing robot, Geckobot, which uses a synthetic dry adhesion mechanism, is more focused on legged kinematics that are similar to a gecko's climbing gait (Fig. 24).[38] It uses a steering and peeling mechanism for high maneuverability and an active tail for robust and agile climbing. Therefore, this legged robot can explore irregular terrains more robustly. The overall weight of the robot is 100g, including the electronic board. The total length is 190mm, the width is 110mm, and the tail is 100mm long. The speed of the robot is 5cm/s during walking on the ground. Geckobot can climb up to 85° in a stable manner on Plexiglas surfaces. However, when climbing at high angles, the speed decreases to 1cm/s due to reasons of stability.

A 400g climbing robot, Spinybot, can readily climb hard surfaces such as concrete bricks and stucco and sandstone walls.[48,52] It employs an array of mimiature spines that catch on surface asperities (Fig. 25). The approach is inspired by mechanisms that are observed in some climbing insects and spiders. Spinybot's feet consist of ten planar toe mechanisms with two spines per toe. The maximum force per spine-asperity contact is 1-2N, and each toe mechanism can deflect and stretch independently of its neighbors to maximize the probability that multiple spines on each foot will find asperities and thereby share the load.

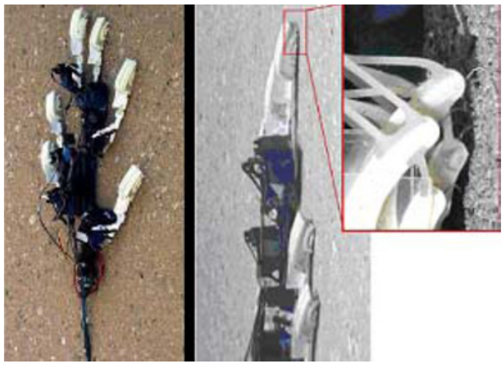


Fig. 25 Spinybot and miniature spines[48,52]

3.5 Rail-Guided Adhesion

In the construction of a building, the basis for the design of an adhesion mechanism for climbing robots can be laid out in advance. One of the representative methods is to install a rail for the sliding of the robot.[87,89,91,93,101,103] The rail can be utilized for grasping to prevent being taken off the surface as well as for a guide along which the robot can slide. Or, on the contrary, to attach themselves, climbing robots can actively utilize some rail-like structure that is already installed on the wall.

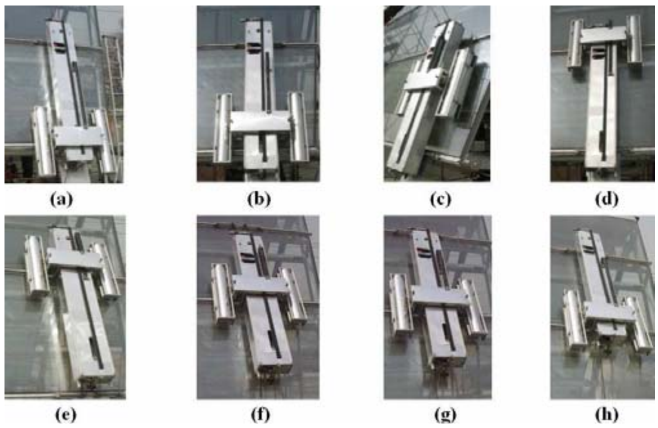


Fig. 26 Climbing test of an outer wall climbing robot[89,92]

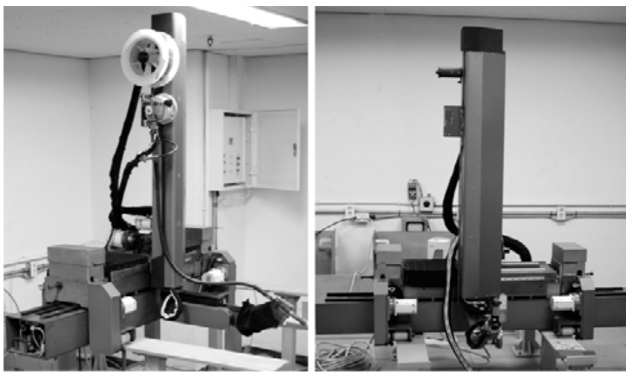


Fig. 27 Mechanism of movement of RRX in the longitudinal direction[87,91]

Table 1 List of climbing robots according to industrial fields with application tasks

Field	Robot	Manufacturer	Country	Application	Locomotion	Adhesion
Construction industry	ROMA I, II	University Carlos III of Madrid	Spain	Inspection	Legged	Gripping
	ROBIN	Vanderbilt University	US	Inspection	Legged	Suction
	CROMSCI	University of Kaiserslautern	Germany	Inspection	Wheel-driven	Suction
	Alicia 1, 2	Universita' degli Studi di Catania	Italy	Inspection	Wheel-driven	Suction
	WallWalker	Kawagwa University	Japan	Wall cleaning	Wheel-driven	Suction
	SIRIUSc	FIFOA	Germany	Wall cleaning	Combined	Suction
	Sky Cleaner 1, 2, 3	University of Hamburg	Germany	Wall cleaning	Translation	Suction
	TITO	IAI/CSIC	Spain	Wall cleaning	Cable-driven	Propulsion
	CAFÉ	DISAM	Spain	Wall cleaning	Cable-driven	N/A
	NINJA-I, II	Tokyo Institute of Technology	Japan	Inspection	Legged	Suction
	GEKKO III	ARECO	Germany	Wall cleaning	Tracked	Suction
	Exterior Wall Painting Robot	Taisei	Japan	Painting	Cable-driven	Rail-guided
Civil infrastructure	Bigfoot	Portech	Germany	Diagnosis	Wheel-driven	Suction
	SM2	Carnegie Mellon University	US	Inspection	Legged	Gripping
	RAMR 1	Michigan State University	US	Reconnaissance	Legged	Suction
	Roboclimber	University of Genova	Italy	Consolidation of rocky walls	Combined	N/A
Petrochemical plant	MRWALLSPECT II	Sungkyunkwan University	Korea	Inspection	Translation	Suction
	MRWALLSPECT III	Sungkyunkwan University	Korea	Inspection	Legged	Suction
	ROBICEN I, II, III	University of Navarra	Spain	Inspection	Translation	Suction
	WCR	Shanghai Jiao Tong University	China	Maintenance	Tracked	Magnetic
	WCR	Dalhousie University	Canada	Inspection	Tracked	Magnetic
	SURFY	Università degli Studi di Catania	Italy	Diagnosis	Translation	Suction
	TRIPILLAR	EPFL-LSRO	France	Inspection	Wheel-driven	Magnetic
Nuclear plant	Robug IIs	City University of Hong Kong	China	Maintenance	Legged	Suction
Shipbuilding	RRX	Seoul National University	Korea	Welding	Translation	Rail-guided
	REST 1, 2	CSIC	Spain	Welding	Legged	Magnetic
	Climbing Robot for Grit Blasting	University of Coruña	Spain	Cleaning	Translation	Magnetic
	NDT robot	London South Bank University	UK	Inspection	Wheel-driven	Magnetic
	Modular Climbing Robot	Universidad de Vigo	Spain	Inspection	Wheel-driven	Magnetic
Aircraft	MACS	California Institute of Technology	USA	Inspection	Translation	Suction
Service industry	MATS	Universidad Carlos III de Madrid	Spain	Human care	Legged	Gripping
	Magnebot	MIT	US	Material handling	Wheel-driven	Magnetic
	Hand-Bot	EPFL-LSRO	France	Object manipulation	Legged	Gripping

A new kind of outer wall climbing robot is proposed for cleaning the complex outer curved surfaces of the National Grand Theater in China (Fig. 26).[89,92] The robot can automatically climb in the vertical direction and clean in the lateral direction. It takes the rails that are mounted on the wall as supports for climbing up and down between horizontal layers and for moving sideways in the layer around the ellipsoidal outer wall of the building. The body consists of the climbing mechanism, the mechanism of movement, two cleaning brushes, and a supporting mechanism. The robot is 3m long, 1.5m wide, and 0.4m high with a body mass of 100kg.

A mobile welding robot, the 'Rail Runner (RRX3),' is capable of freely moving in both transverse and longitudinal directions, and performs welding tasks in double-hulled structures.[87,91] The mechanism of movement of the RRX, which is able to move freely in double-hulled structures, has two functions: to move in a longitudinal direction through driving wheels that use longitudinal faces as 'rails' and to move in a transverse direction by sliding along the supporting longitudinal faces using extension arms (Fig. 27). The body of the RRX is composed of a six-axis mobile platform that supports the RRX mechanism of movement and a six-axis welding robot. The full size of the robot is 1825x495x 569mm^3, and the weight is 250kg.

4. Applications of Climbing Robots

Robotic systems can perform various tasks even in extremely hazardous environments that are often accompanied by high altitudes, high temperatures, high pressures, radiation, and so on. Therefore, the ability of climbing robots to relieve humans from hazardous work has caused a great deal of interest to researchers over the past few decades. Industrial fields where climbing robots can be usefully deployed are classified as follows: construction, civil infrastructure, petrochemical plants, nuclear plants, shipbuilding, aircraft inspection, service sectors, and so on. Table 1 presents a complete list of climbing robots according to the above-mentioned classes with application tasks. A few climbing robots that are listed in the table are still being improved for more practical applications and some of the robots can be applied to more than one field interchangeably.

5. Concluding Remarks

In this paper, a survey of climbing robots with high potential that have been applied in various industrial fields and investigated for scholastic purposes has been presented. With respect to the locomotive and adhesion mechanisms, which are necessary requirements for climbing, climbing robots are classified into six and five groups, respectively. Along with a brief outline of each group, a few representative examples that describe the unique characteristics have been introduced. Further, according to the industrial fields that adopt climbing robots, a complete table of climbing robots has been provided along with specific application tasks. Many light-weight climbing robots have less payloads causing low applicability to practical tasks that involve carrying various equipment. Otherwise, they are heavy of weight and slow owing to the increase in their size for employing rigid and complex mechanisms for large payloads and high mobility, which leads to low operational efficiency. In terms of further research in the future, it is important to develop climbing robots with such abilities as an appropriate payload, high speed of operation, and high energy efficiency.

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