



Climbing Robots, Their Types, Applications, How They Work and Their Characteristics

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Abstract

This research clarifies the most important principles under which wall-climbing robots operate. Two important aspects must be examined in the study of this type of robot. The first aspect is the adhesion method, which has been analysed extensively over the years with multiple approaches. The second aspect is the movement method, which may or may not be integrated with the adhesion method. Research published in the last two decades has divided these robots into five main types and another subtype, each of which provides high efficiency in a specific environment and application. However, the efficiency decreases in others. For example, a robot with suction cups needs a smooth surface, a robot with ducted fans requires a surface that is free of holes, and a robot with magnetic adhesion needs a metal surface. Two robots, one utilising bioinspired adhesion and the other relying on rope and/or rail grabs, function on different surfaces and perform separate applications. This study determines the most important and effective designs, along with their strengths and weaknesses. The suitable applications and environments of these robot are also presented.

Keywords: *Climb; Suction; Pressure; Bio Robot*

1. Introduction

The rise in population and the development of all branches of engineering have driven the need to resort to vertical buildings (for residential and industrial uses), such as oil tanks, nuclear energy towers and communications towers. Hence, designing robots that are capable of climbing to accomplish tasks is urgently needed for tasks that are mostly difficult, dangerous and expensive for humans. This field is of great importance in the development of many engineering and economic fields. However, the main problem is the robot's method of adhesion (without sacrificing freedom of movement). Each material requires a different method of adhesion. For example, surfaces differ in terms of density and roughness; they can be made of glass, metal or wood, with or without holes, as well as other surfaces to consider [1-3]. The study

of this type of robot is not new. For instance, designs dating back to the 60s of the last century were prepared by Akira Nishi and Hiromori Miyagi [4]. However, research into this type of robot has increased recently because of its urgent need, and many studies and designs have appeared in the past two decades [5]. Therefore, dozens of designs are available. The most important and effective ones, along with the selection method to suit specific needs and the actual environment, are discussed in this work. The second section presents the most important designs and research in this field, while the third section mentions other types of designs that are not commonly applied. The fourth section contains a comparison between designs along with their strengths and weaknesses, in addition to the future outlook. The fifth section contains a summary of the research.

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2. Popular Designs and Research

Many common methods are used for designing climbing robots. However, adhesion methods can be divided into five main methods that have inspired other designs.

2.1. Adhesion Using Suction Cup

This design is considered one of the oldest types. A set of rubber cups is placed on a surface to create adhesion. Then, the air is emptied between the cup and the surface to create a pressure difference that leads to adhesion. Many approved designs vary depending on the number of arms or the method of emptying air. However, the main problem with this type is that it is only suitable for smooth surfaces, such as glass and painted surfaces. This type is also very slow. The design of the cups allows air to exit easily and restricts its entry, which generates a high level of negative pressure between the robot and the surface. However, the risk of air leaking into the cup remains, which may lead to the cancellation of adhesion. This issue can be reduced by using the vacuum pump principle, which involves continuous emptying to maintain pressure. This type of method is analysed using Bernoulli's principle to determine the capacity required to sustain the pressure [6]. W. Wang et al. [7] proposed that the creation of vibrations to generate a continuous vacuum, as shown in Figure 1. This effect is achieved by generating a sine or square wave and controlling its amplitude or frequency, resulting in an almost continuous vacuum space between the cup and the wall. As shown in Figure 2, Kawasaki et al. [8] examined the possibility of relying on a genetic algorithm to determine the path of attachment and separation for six legs that have one degree of freedom. These legs can move on smooth surfaces only because negative pressure is generated for adhesion. Moreover, one of the edges of the cup is moved to separate it from the surface. Moving one of the edges of the cup causes air to leak, which causes an imbalance in pressure and eliminates adhesion. Luk et al. [9] determined a solution to the problem of surfaces that contain obstacles. They considered an ideal design for rough, flat and horizontal surfaces with obstacles; the design allows the object to move without tripping or colliding with any object, as shown in Figure 3. This solution is possible because of the presence of a wide range of sensors and ultrasound, in addition to the use of artificial intelligence in this design. Additionally, Briones et al. [10] aimed at solving the weight problem; their design is light and small,

which makes it suitable for nuclear tower applications that require high flow. This robot consists of two identical bodies connected by pneumatic joints in addition to two air cups in each part, as shown in Figure 4. These cups work alternately with each other for the robot's movement and adhesion, thus solving some of the typical problems of suction cups, such as low speed and heavy weight due to the vacuum systems and attached pipes. A group of suction cups is added to the same movement path. Therefore, the movement force becomes the same as the adhesion force in a design called the Crawler Adhesion Cup. This design is useful in terms of speed but has limited weight and can only be used on small robots [7]. Hao Yang et al. [11] emphasised that in addition to the large area of movement generated by this design, the ability to move in all directions (with rotation) is an important feature. This type of negative suction can be considered one of the most noise-free methods (compared with other methods), in addition to being less needed than other types.



Fig. 1. Vibrating suction method [7]

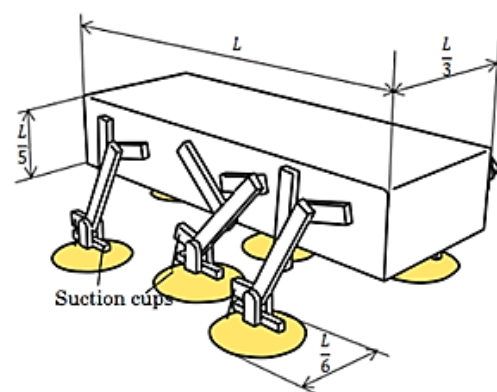


Fig. 2. Six-leg design with passive suction cups [8]

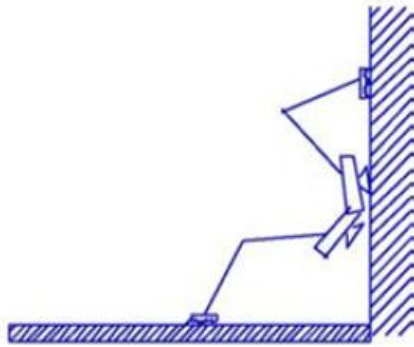


Fig. 3. Floor-to-wall transfer sequence [9]

2.2. Ducted Fans (Negative Pressure Adhesion)

In this design, a fan (or several fans) is added to the robot to assist in adhesion to the wall. Then, the robot is moved using separate motors. This type has several designs. The main idea is to design a robot that resembles a cart with the addition of a source of adhesion in the middle. Electric ducted fans (EDFs) are often used. These engines are used in jet aircraft, while a regular fan with an exhaust cover designed to direct the air can also be added, along with the design of a sealed area (room) between the robot and the wall [12].

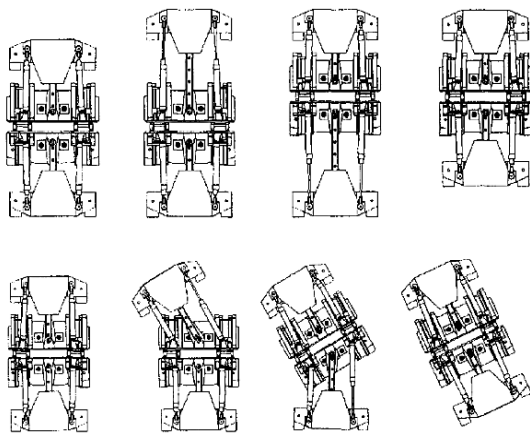


Fig. 4. Relative positions of the two bodies of the robot [10]

This design generates two sources of adhesion between the robot and the wall. The first is the thrust force produced by the fan (or motor), which leads to the generation of the second source (which is more important). Drawing air from the insulation room to the outside using the exhaust leads to the generation of a negative pressure (suction) area between the robot and the wall [13]. The area increases as the

thrust force of the fan increases because of the air being discharged from the room (which is tightly insulated with the wall). One of the most important features of this design is effectivity on any surface (wood, concrete, magnetic, etc.). Complete adhesion between the robot (the isolation room) and the wall is not required, as is the case in the suction cup type. This type of design may be ineffective on surfaces that contain many holes [14]. Critical suction, as explained by Xu et al. [15], depends on the pulling and pushing of air to ensure its adhesion to the robot. They also outlined the appropriate mechanical (force analysis) and electrical calculations. Additionally, Fallah et al. [16] attempted to find the ideal dimensions of the robot, including the area of the nozzle, in addition to calculating the speed and pressure and comparing them with previous results. The appropriate number of nozzles for the design was also determined. Meanwhile, Figure 5 presents the design and research of Shujah et al. [17]. Their research was directed towards creating a robot that can be controlled wirelessly. A robot consisting of a motorised pusher is used to generate the adequate pressure for adhesion. Precautions must be taken to ensure that the impeller size is as small as possible and does not touch the wall to ensure the robot's freedom of movement.

While most researchers have used a circular shape for the discharge opening, Zhou et al. [18] suggested using a square shape. They asserted that the most important problems are related to the circular design. As such, they compared circular and square designs and found that the load of the square design exceeds the circular design by 18%, in addition to its ability to cross large canyons. Meanwhile, the circular shape is maintained by Praveen Sekhar et al. [19]. This configuration relies heavily on Bernoulli's principle in cylindrical designs to control air speed and pressure and increase efficiency. In addition, the cylinder helps reduce propeller thrust losses (losses due to propeller design). The appropriate application of this research involves monitoring concrete cracking using a camera. This design consists of a four-wheeled cart, a camera location and a protruding cylinder for a propeller.

A significant number of scientists are studying vortex climbing robots, which is shown in Figure 6. Research is aimed towards designing a robot with a lightweight structure and the capability to carry very heavy loads. An EDF is added to the robot for high adhesion strength. In addition, the robot is controlled via the proportional integral derivative (PID) controller [20-23].

With the emergence of artificial intelligence, Yi Fang et al. [24] suggested the use of a genetic algorithm to find the appropriate and most efficient design for a climbing robot. Several aspects of the design are studied in this algorithm, such as the shape and dimensions of the pressure chamber and the number and angle of the blades. Koo et al. [25] abandoned the idea of four equal wheels through a design called LARVA, which has two front wheels to pull the robot, in addition to a pressure chamber and a fan. The research contains many calculations for strength analysis and air leakage, which is the most crucial problem in this design. Meanwhile, J. Liu et al. [26] retained the four wheels in their design but added belts to the drive side of the clutch instead of regular wheels, as can be seen in Figure 7. This configuration adds to the vehicle's ability to manoeuvre and move on various surfaces.

2.3 Magnetic Adhesion

Factory tanks and extraction sites are the best environment for this design. The robot relies on magnetic forces to stick to metal surfaces only. The aforementioned designs, namely, suction cups and ducted fans, often require a continuous source of power, thus presenting a problem [27].

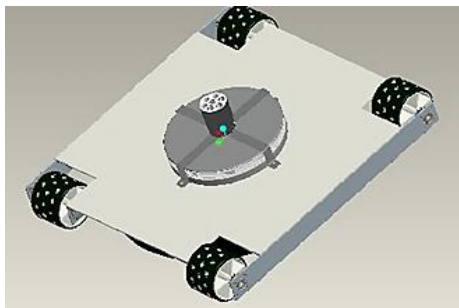


Fig. 5. Semiautonomous wall climbing robot using vacuum suction adhesion [17]

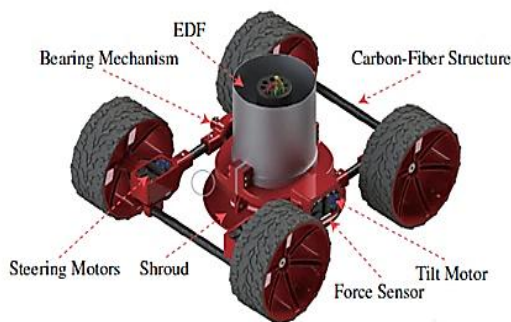


Fig. 6: Graphical representation of the vortex climbing robot setup [23]



Fig. 7. Integral slipping model [26]

The most important goal in robots is to be as independent as possible to ensure their operation in the largest possible area. Therefore, this design is ideal because it relies on the installation of magnetic tips on the robot regardless of its mechanical design and controlling them using a separate battery connected to it. This type of robot is controlled by giving orders to turn the magnetic parts on and off (supplying or disconnecting the current, respectively). This feature can simplify the design and control system [28]. However, the robot may slip if the surface of the metal is not sufficiently magnetised. In addition, this design is not valid on nonmagnetic surfaces (concrete, wood or glass). Therefore, the use of this type is often limited to industrial environments (oil and gas tanks). This method of adhesion is very helpful in selecting the appropriate structure; depending on the purpose of the robot, it may be shaped like an insect (worm) or a cart [29].

The use of magnets for adhesion has given flexibility to designers and researchers because it has allowed the creation of different forms of robots. For example, K. Wang et al. [30] developed a robot with four joints. When this robot moves, one joint is in an active state, while three joints are not. The research also attempted to find the appropriate ability to rotate the joint. Additionally, Kotay et al. [31] designed a robot that can move in all directions and avoid any obstacle ahead. The research clarified and sought the appropriate angle for this model.

G. Lee et al. [32] focused on a robot that uses chains for movement and magnets for stability. This design can hold more than 4 kilograms while walking at a right angle, as shown in Figure 8. This

robot can also move between corners with ease. Moreover, the traditional design of robots (a cart that sticks to the magnets) is commonly used [33,34]. Flexibility can be added to the structure by adding multiple limbs that move on metal surfaces using magnets, as Bandyopadhyay et al. [35] did in the design shown in Figure 9. Different designs have also been developed [36], such as a robot of three similar parts connected by springs and motors to generate the energy needed for movement and cohesion, as seen in Figure 10 [37]. In addition to a tail at the end of the robot that is used for movement, this design can bear very heavy weights and change the torque of the motors according to what is appropriate for the surface and weight [38].

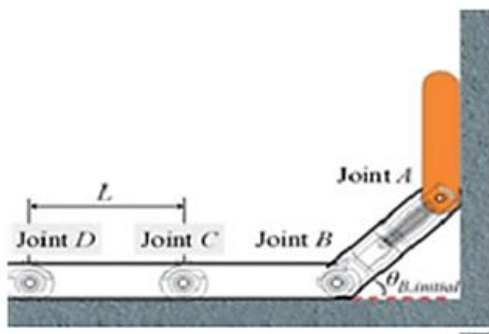


Fig. 8. Set-up to calculate the inverse kinematics. The first link contacts the wall for the first time [32]

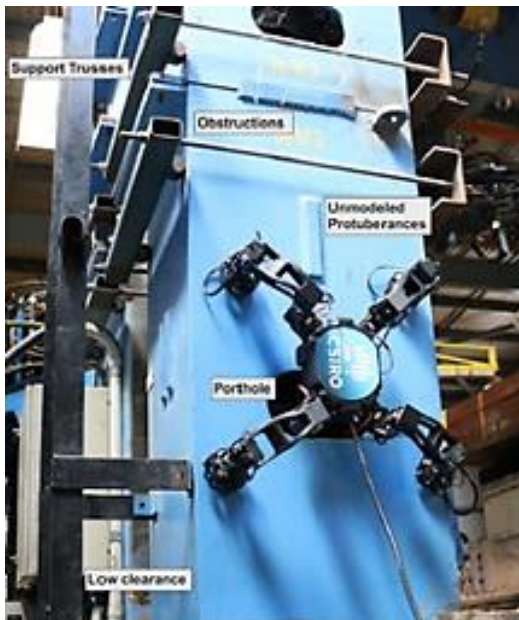


Fig. 9. Versatile multilimbed inspection robot [35]



Fig. 10. Assembled combot prototype [36]

2.4. Bioinspired Adhesion

The study of living organisms has long been a curiosity for scientists, and the field of robotics has benefited greatly from such research given that many designs can be drawn from nature. The first and most important feature is the design of limbs that are similar to those of geckoes, cockroaches and worms [4]. These animals can carry 40 times their weight with rapid movement and strong adhesion to any angle [39]. The gecko’s method of adhesion and the ability to maintain its cleanliness in any environment (no dirt from the environment sticks to it) remained unknown for many years (despite the emergence of many hypotheses); its adhesion depends on the direction: it is strong in one direction but weak in the opposite direction by about 1:100 [3]. The gecko’s ability to stick to surfaces lies in its limbs, which have microscopic properties in addition to the nanoscale spatula-like hairs, as seen in Figures 11 and 12. This component conforms to various surfaces to generate van der Waals forces, which are responsible for adhesion with a coefficient that can reach 8 to 16 (the adhesion coefficient is the ratio of preload to pull force and is a relative measure of adhesion strength) [40-44]. In addition to geckoes, other applications for bioinspired adhesion include using claws, copying the structures of living organisms that can climb at a certain angle or applying dry rubber that works according to the same principle as crawlers when climbing [45-47]. These designs borrow many characteristics, methods or structures from living organisms. Funatsu et al. [48] posited that small objects have low gravitational influence, allowing free movement on vertical surfaces while providing a high force for this size. Their research developed a hexapod robot with small centimetre-size claws, which are similar to insect claws, for climbing. Daltorio et al. [49] also examined the importance of added joints to small climbing robots so these robots can move from vertical surfaces to horizontal surfaces at an angle of 90 degrees; in this design, the

movement of the robot resembles the movement of a cockroach. Their research also attempted to find the appropriate placement of the joint (in the middle or on both sides). Inspiration from living creatures is almost endless, as seen in the variations drawn by many studies from the external appearance of some insects (the gecko). Such variations include the difference in the design and operation of two robots, both of which walk like a gecko. Alternatively, one design may mimic one part of the insect, such as the tail. The first can be controlled by a single motor, while the second can be controlled by a shape memory alloy, making the size variable [50], [51]. In [52-54], the way the gecko moves and climbs is imitated and developed; thus, the robot has four legs and a flexible tail. This design can move on different surfaces at an angle of up to 85 degrees, as shown in Figure 13. The method of sticking limbs to surfaces was also adopted, including the use of adhesive biological tapes in a small-sized robot for exploration and surveillance, which has a very similar function to a vehicle. The legs are equipped with adhesive straps for climbing. These tapes, as shown in Figure 14, are characterised by their ability to attach and separate easily and quickly because they are made of organic materials that are similar to those found in the legs of insects [55-57]. Rubber materials were also added to the edges. Therefore, this design is distinguished by its ability to move around sharp turns and different angles using three legs, each of which contains rotating joints that are moved by two motors. The adhesion process is performed using a dry rubber material that adheres strongly to glass surfaces [58], [59]. The inspiration from insects did not stop with the gecko only. Researchers discovered beetles' and caterpillars' movements and attempted to simulate these movements. Wile et al. [60] designed a robot with six legs and a motor, where three legs work together. The method of adhesion relies on maintaining tension between the legs as they move along the web, similar to the way beetles climb. Wang et al. [61] designed a method to control a robot that resembles a caterpillar in shape and movement. The robot consists of seven joints that

change alternately to propel the robot, as well as sticky parts at each end.

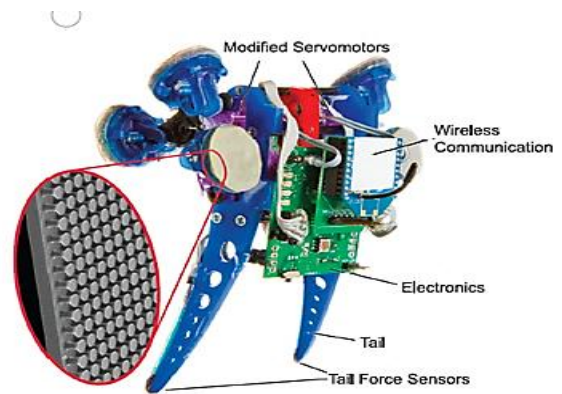


Fig. 11. Versatile Multilimbed inspection robot [52]

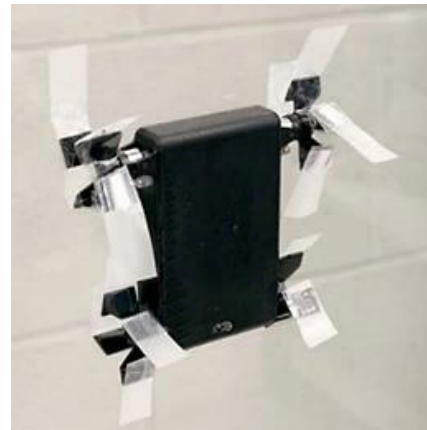


Fig. 12. Small wall-walking robot with compliant, adhesive feet [55]

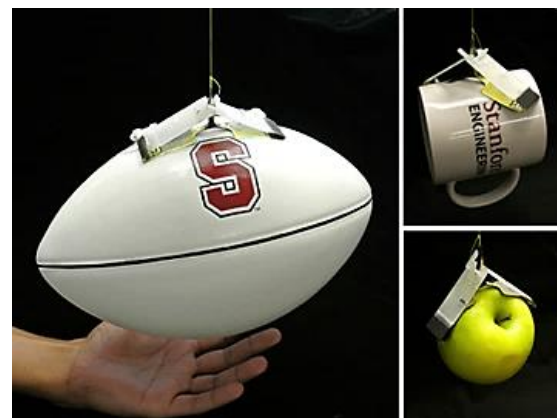


Fig. 13. Gripper picking up common objects [40]

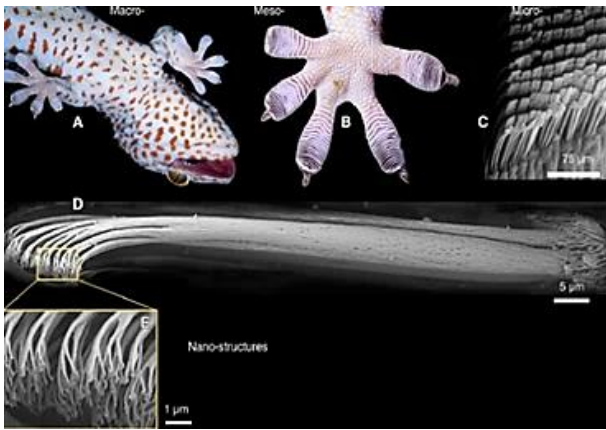


Fig. 14. Structural hierarchy of the gecko adhesive system, from mesoscale features on the feet (B), to microscale setae (C, D) and nanoscale spatulae (E). Reproduced with permission [40].

2.5. Rope and/or Rail Gripping

This method may be considered one of the oldest methods used for climbing. A rope or group of ropes that are controlled by changing their lengths using motors or complex systems is used. The main advantage of this design is that it is considered the safest and most reliable configuration compared with other designs. Therefore, it is commonly used for human safety, such as for workers cleaning building facades and maintenance workers on high towers. However, the obstacles to this design are its limited flexibility in terms of freedom of movement because it can only work in its own space, in addition to the required installation and maintenance [6]. Furthermore, Elkmann et al. [62], [63] designed a robot that is not so much a climber but rather a hanging robot. The main purpose of this robot is to clean and maintain building facades using a cleaning cart or robot attached to a set of ropes extending from the roof of the building, which provides movement in one direction (one axis, upward or downward). Horizontal movement is achieved by tying ropes from above to a carriage running on rails. This design provides a stable workspace and the ability to hold high amounts of weight, as seen in Figure 15.



Fig. 15. Facade cleaning robot for a high-rise building in Munich, Germany [63]

3. Other Designs

In addition to the five designs of climbing robots, other designs are difficult to classify into any of the five main methods (mentioned above) because their methods of adhesion to surfaces differ from the five methods and from one another. The movement of these robots depends on a certain mechanism.

3.1. Tank-like module-based climbing robot using passive compliant joints

The design of tank-like module-based robots depends on its movement to distribute loads between two parts with a joint between them, in addition to the tail, which propels the robot as a whole. As for the method of adhesion, it depends on the friction that occurs between the wall and the dry rubber material that acts as wheels, as shown in Figure 16 [64].

3.2. Robotic rock-climbing using computer vision and force feedback

Rock-climbing robots are designed to obtain a low-cost robot with simple mechanics to resemble a frog's movement. This robot relies on random protrusions (bumps or voids) in the wall to climb using its four frog-like limbs. Additionally, an algorithm determines the style of movement based on an analysis of the previous information, as shown in Figure 17 [65].

3.3. Serpentine Robot Moves and Postures

The serpentine robot is not a climber on regular walls and surfaces. However, it can be considered a

successful climber (like a snake) if a good environment is provided. The design consists of a tube or stick wrapped around the robot, as shown in Figure 18. The movement of this robot and its joints are studied [66].

3.4. Climbing Technique of the Cleaning Robot for a Spherical Surface

Researchers [67-69] have proposed a solution to the problem of modern circular buildings, where finding a safe and effective method of cleaning is difficult. One study uses a rail-guided climbing mechanism to make the cleaning robot move safely around spherical building surfaces and between their levels. The research also suggested how the robot can change its dimensions to fit the new level.

4. Characteristics of Each Design and Futuristic Outlook

The diversity of industrial and civil environments requires the discovery of methods and designs that are effective and compatible with the environment. These points are listed in Table 1.

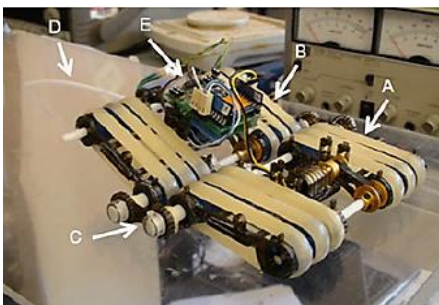


Fig. 16. Tank-like module-based climbing robot using passive compliant joints [64]

Table 1, Properties and Disadvantages of Each Design Type

Design type	Properties	Disadvantage
Suction Cup	Older design (since the 1960s) Relying on creating a vacuum (pressure difference) in a group of cups Many ways and designs of movement	Only works on smooth surfaces. Slow Air leakage
Ducted Fans (Negative Pressure Adhesion)	The design resembles a cart. It works using an engine (or more) placed in the middle. Two sources of adhesion (push and pull) Movement by separate motors	It does not work if the surface has holes.
Magnetic Adhesion	Works on all surfaces It works by turning on or off a magnetic field (by current).	It only works on metal surfaces.

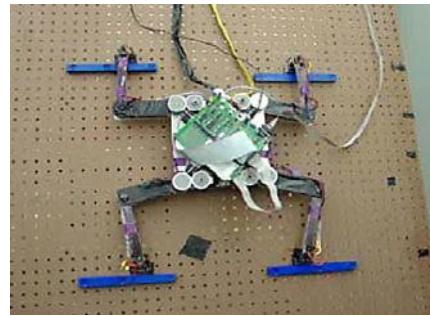


Fig. 17. Robotic rock-climbing using computer vision and force feedback [65]

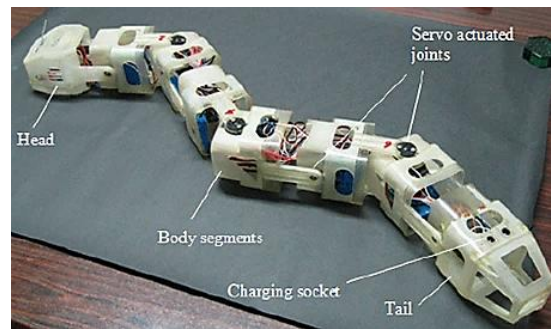


Fig. 18. Serpentine robot moves and postures [66]

	Many designs or structures are possible.	
Bioinspired Adhesion	Powered by a separate power supply It is based on nanotechnology. It can carry many times its weight. Strong adhesion in one direction and weak in the other	Challenging mechanical design High cost
Rope and/or Rail Gripping	One of the oldest methods It is based on a set of fixed engines. More reliable	It requires maintenance and installation. Fixed work space Over time, the dimensions of the rope may change.

Table 1 shows the possibility of using suction cup robots for medium weights. A fairly acceptable movement is achieved. While ducted fans are preferable when the need for manoeuvring and movement is widespread, robots with magnetic adhesion remain ideal for metal surfaces because they have very high adhesion strength, in addition to multiple methods of control. The use of bioinspired adhesion is also preferred in precise and sensitive applications which require high precision in movement while carrying light weights. For opposite applications which require very heavy weights, the rope and/or rail gripping method is preferred because of its remarkable ability (compared with other designs) to carry heavy loads.

Attaining the ideal design that is suitable for a wide number of surfaces will become increasingly possible with the development of other sciences and their inclusion in this field, especially because this type of robot is needed in present and future applications. For example, integrating artificial intelligence into the development of robots may make a substantial difference. Kondratenko et al. used a neuro-fuzzy approach to determine the appropriate amount of force for the adhesion of a magnetic robot [70].

This innovation can save a large amount of energy in addition to facilitating smooth movement. In addition to artificial intelligence, the development of processors and structures (the materials from which the robot is made) can lead to the production of robots with reduced weight and enhanced efficiency.

5. Conclusions

Limiting the applications of climbing robots is difficult. This field is evolving with the development of technology, in addition to reducing the rate of injuries and deaths among maintenance workers significantly. These robots are almost essential in any vertical environment (climbing

towers, tanks, walls and buildings) and application (maintenance, welding, monitoring and processing), in addition to their use in security operations. Working on designs for these robots is not a recent undertaking. The first designs were developed in the 60s by Nishi Company, which proposed a design based on a single vacuum suction cup. Research remains ongoing in this field because of the constant and changing needs for robots. Carrying heavy weights and ensuring accuracy and speed in movement are not always the most important requirements because these aspects also change according to the application. However, the main purpose of researching climbing robots is to minimise cost (reduce manpower) and increase freedom of movement while maintaining the ability to carry heavy weights for applications that humans may not be able to carry. Therefore, researchers must select among multiple designs with different characteristics that suit various applications and target environments. As such, each design has strengths and weaknesses, which can be determined depending on the application. Some features that may be considered useful in one application may be a hindrance in another. With the development of science, other effective and adaptable designs may emerge. The development of materials engineering will help in designing structures with reduced weight and increased resistance to temperature. Artificial intelligence can also be added so that the robot can select the most appropriate and least expensive process.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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روبوتات التسلق، أنواعها وتطبيقاتها، طريقة عملها وخصائصها

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المستخلص

تهدف هذه الورقة البحثية إلى توضيح أهم المبادئ التي تعمل بموجبها روبوتات تسلق الجدران. لدراسة هذا النوع من الروبوتات، تتم دراسة جانبيين مهمين. الجانب الأول هو طريقة الالتصاق، والتي درست وبحثت على نطاق واسع على مر السنين بمناهج متعددة. الجانب الثاني: هو طريقة الحركة، والتي قد تكون أو لا تكون متكاملة مع طريقة الالتصاق. قسمت الأبحاث المنشورة في العقدين الماضيين هذه الروبوتات إلى خمسة أنواع رئيسية و أنواع فرعية أخرى، يوفر كل منها كفاءة عالية في بيئة وتطبيق محدد، وتنخفض الكفاءة في بيئات وتطبيقات أخرى. على سبيل المثال، يحتاج روبوت كأس الشفط إلى سطح أملس، ويحتاج روبوت المراوح الأنبوبية إلى سطح خالٍ من الثقوب، ويحتاج روبوت الالتصاق المغناطيسي إلى سطح معدني. الروبوتان، أحدهما يستخدم الالتصاق المستوحى من البيولوجيا والآخر يعتمد على الحبل و/أو التمسك بالسلك الحديدية، يعملان على أسطح مختلفة ويقومان بتطبيقات منفصلة. في هذه الورقة، ولتوضيح ذلك، يتم تقديم أهم التصاميم وأكثرها فعالية، إلى جانب نقاط قوتها وضعفها، بالإضافة إلى تطبيقاتها وبيئاتها المناسبة.