Overview of the current status and development trend of wall-climbing robots

ABSTRACT

The rapid development of wall-climbing robots, wall crawling robots have received great attention from all walks of life and have been widely used in many fields. Through the analysis of the existing wall climbing robots related applications, the wall climbing robots are divided into crawler, wheeled, foot and hybrid according to the moving mode, and the wall climbing robots with different moving modes are reviewed through the literature research method; the wall climbing robots with different adsorption modes such as vacuum adsorption, magnetic adsorption, and special adsorption are compared, and the current status of research on the wall climbing robot's self-adaptive technology and the existing problems are introduced, and it summarizes and analyzes the development trend of wall-climbing robots in industry, military and other fields, analyzes the characteristics of different adsorption methods of wall-climbing robots, and summarizes and predicts the development direction of wall-climbing robots.

Keywords: Wall-climbing robot; Mobility mode; Adsorption mode; Development trend.

1. INTRODUCTION

With the continuous development of science and technology, people is awareness of the high-risk work environment has increased, robots instead of manpower to complete high-risk work has become a common development trend. [1-4]Wall-crawling robots is a branch of industrial mobile robots and special robots research, which, because of its effective wall adsorption and mobile characteristics, can be equipped with a ride on the reconnaissance, testing, maintenance and other equipment to complete the task of high-altitude elevation operations, in the military, Ships, wind power and other fields have a broad application prospects, in 2015, "Made in China 2025" plan promulgated, China's industrial robots into the rapid development of the period, many research departments focus on wall climbing robot research, in the basic theoretical knowledge, structural optimization of the design of the mechanism coordinated control system and other aspects of the exploration, the depth of fusion of sensors and other technologies, to achieve the climbing robot intelligent, instead of manual high-efficiency research. This paper combines the research results in the field of wall climbing robots in recent years, summarizes and analyzes the research status of different types of robots, discusses its key technologies and development direction, and provides effective reference for the future engineering design of wall climbing robots. [5-8]

2. ANALYSIS OF THE CURRENT STATUS OF WALL-CLIMBING ROBOT RESEARCH

Wall climbing robot is mainly composed of adsorption mechanism, mobile mechanism and drive mechanism, in which the adsorption mechanism and mobile mechanism play a vital role in the operation. Wall-crawling robot can be divided into: leg and foot, wheeled, tracked, composite, etc. according to the mobile mode. According to the adsorption method can be divided into: magnetic adsorption, negative pressure adsorption, bionic adsorption. The following is the introduction of domestic and foreign wall climbing robot movement and adsorption method.

2.1 WALL-CLIMBING ROBOTS WITH MOBILE TECHNOLOGY SOLUTIONS

Mobile technology is wall climbing robot to different operating locations for the corresponding operation, the current wall climbing robot can be divided into the main mobile mode: leg and foot, wheeled, tracked, composite and so on.

2.1.1 LEGGED WALL CLIMBING ROBOT

The mobile mechanism of the legged-footed wall-climbing robot generally integrates the adsorption module in the sole of the foot, and realizes the wall movement through the alternating adsorption and movement of multiple feet, which is highly adaptable to the wall surface, and can cross-walls or obstacles on the wall surface. Because it can be adsorbed on the wall by multiple feet at the same time, the reliability of adsorption is high. There are two-legged, four-legged, six-legged or eight-legged, generally the more the number of feet, the more degrees of freedom of the robot, the more flexible the movement, but at the same time the heavier the quality, the more complex the structure and control. Changchun University of Science and Technology developed a six-legged spider bionic wall-climbing robot shown in Figure 1, the wall-climbing robot is mainly composed of the robot shell, leg movement mechanism, end adsorption system. The overall size of the six-legged wall-crawling robot 420 * 450 * 200mm, the maximum speed of 3.8m/min.[9-10] In 1995, the UK Portsmouth University developed wall-crawling robot shown in Figure 2, the robot adopts the imitation of the eight-legged movement of the crab and the spider mechanism, the ability to cross the obstacles, the load is larger, but at the same time, the quality and size of the robot is also larger. The robot has high adsorption reliability, slow movement speed, poor payload, strong obstacle-crossing ability, suitable for smooth work surfaces and complex control system.[11]

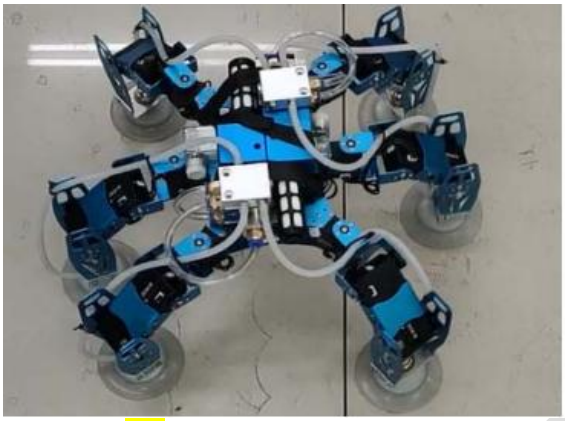

Fig. 1. Six-legged wall-crawling robot

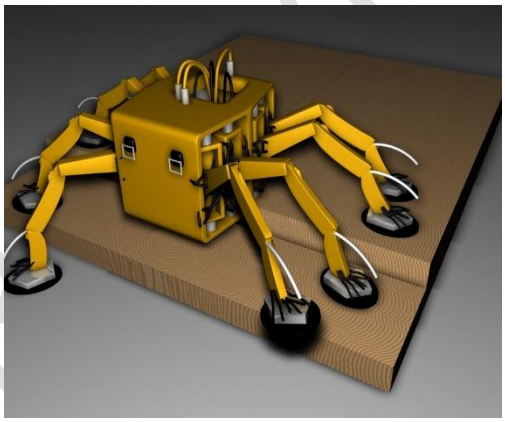

Fig. 2. Eight-legged wall-crawling robot

2.1.2 WHEELED WALL-CLIMBING ROBOT

Wheeled wall-climbing robot is generally composed of movement mechanism (wheels) and adsorption mechanism and each other as independent unit, usually adopting a negative pressure adsorption type. Italy D.Longre team developed a ALICIA wall-crawling robot shown in Figure 3, the wall-crawling robot uses a vacuum cleaner centrifugal fan as the whole adsorption system of negative pressure hair device, ALICI wall-crawling robot overall weight 4.6kg, the shape of the disc diameter size is 290mm, height of 180mm, maximum moving speed of 2.3m/min, maximum load capacity of 2.8kg.[12-13] In 2008, the wall climbing robot Cromsci developed by Kaiserslautern Technology in Germany uses multi-cavity adsorption, as shown in Figure.4. The small body of the robot is a round nga-shaped structure, the chassis has three universal wheels, huh to achieve a full range of movement, the force sensors on the wheels can be used to identify whether they are in a balanced state. Seven small sealed chambers at the bottom of the robot are connected to a large negative pressure chamber at the top to create negative pressure and provide adsorption for the robot. The shape of the disc diameter size is 1053mm, height of 560mm, the maximum speed of movement is 4.3m/min, the maximum load capacity of 6.3kg.[14-15] The above two types of adsorption reliability, slow movement speed, payload is small, poor obstacle-crossing ability, maneuverability.

Fig. 3. ALICI wall climbing robot

Fig. 4. Cromsci wall-crawling robot

2.1.3 CRAWLER WALL CLIMBING ROBOT

Crawler type wall crawling robot takes crawler as the moving mechanism, mainly has magnetic adsorption, negative pressure adsorption in two ways, as shown in Figure 5 is a kind of ship descaling crawler wall crawling robot Hydro-Crawler, which was developed by American CHUKAR company in 2006, it adopts double row crawler structure, there is a permanent magnet installed in each crawler magnetic adsorption unit, and it can stabilize and adsorb 203kg body with magnetic adsorption force, its maximum traveling speed reaches 60mm s, and the one-time cleaning width is 480mm. Magnetic adsorption force can be self-weight 203kg body stable adsorption in the ship wall, its maximum travel speed reached 60mm / s, a one-time cleaning width of 480mm.[16-17] The U.S. ICM company did not count of a wall-crawling robots using negative pressure adsorption mode, in which the crawler as a mobile mechanism, the use of the distribution of tracks in the periphery of the negative-pressure chamber mesh cavity sealing, as shown in Figure 6. This sealing method is characterized by a rolling motion between the sealing unit and the wall surface, with less frictional resistance, and the sealing material is not easy to wear out.[18] The support plate on the top can assist the robot to realize the transition between the floor and the wall. The robot is loaded with large loads and, due to the soft and thick tracks, is able to adapt to wall surfaces with a certain degree of cracks and grooves. The former is suitable for metal surfaces and the latter two for concrete surfaces. Both types have high adsorption reliability, faster movement speeds, higher payloads, and average obstacle-crossing capabilities.

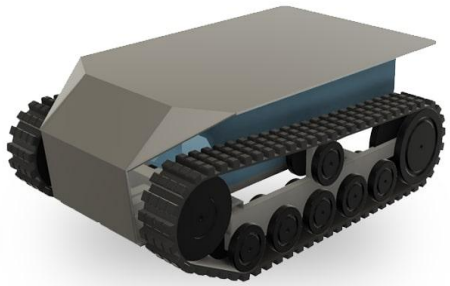

Fig. 5. Crawler magnetically attached wall climbing robot

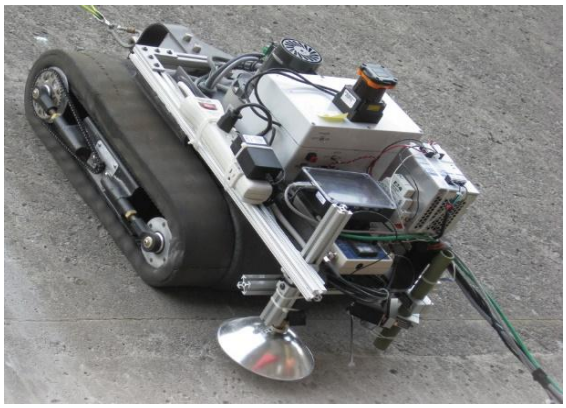

Fig. 6. ICM wall climbing robot

2.1.4 COMPOSITE WALL CLIMBING ROBOT

Composite wall-climbing robots are a mixture of two or more modes of mobility, allowing the robot to combine the advantages of different mobility mechanisms.In 2004, a robot was developed in Germany for glass curtain wall cleaning as shown in Figure 7. The robot SIRIUSc uses a combination of rope and sliding frame mobility. The roof of the lifting device to realize the robot in the wall of a wide range of movement, the robot body on the sliding frame to achieve a small range of movement of the robot, can improve the positioning accuracy of the robot.[19] Shenyang Institute of Dynamic Chemistry battered a wheel-foot composite wall climbing robot, shown in Figure 8. AIR-III biped uses a planetary wheel system mechanism, the two wheel system is connected through the rotating arm, the bottom of the two feet are vacuum suction cups and sealing chamber.[20] The robot has two motion modes: wheel motion, biped motion and compound

motion. Through the wheel system of the flip line with the foot adsorption can be realized bipedal movement: sealing cavity is installed with a wheeled mobile mechanism, wheeled movement can be realized; wall climbing robot at the same time for the above two modes of movement, that is, the composite movement. This type of adsorption is highly reliable, the former movement speed is faster, the latter is slow, both have the characteristics of small load and poor adaptation, while the former needs a traction rope, the latter needs a larger driving force.

Fig. 7. SIRIUSc wall climbing robot

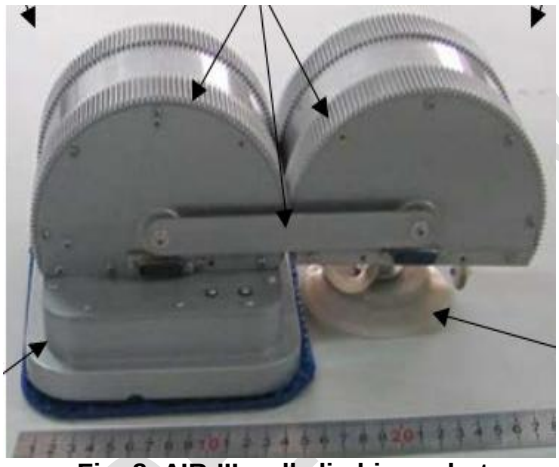

Fig. 8. AIR-III wall climbing robot

2.2 WALL CLIMBING ROBOTS WITH DIFFERENT ADSORPTION TYPES

Adsorption technology is the prerequisite for wall climbing robots to work on the wall, according to the different principles of adsorption, the adsorption methods of wall climbing robots can be divided into: magnetic adsorption, negative pressure adsorption, bionic adsorption. Each adsorption method has its own characteristics and has greater limitations.

2.2.1 WALL CLIMBING ROBOT WITH MAGNETIC ATTACHMENT

Magnetic adsorption is mainly applied to surfaces of magnetically conductive materials (e.g., oil tanks, boiler water-cooled wall drains,). Magnetic adsorption can be combined with various moving methods, reliable adsorption, energy saving. However, the control of adsorption force is more difficult, the adsorption force is affected by the unevenness of the wall surface, and magnetic adsorption is only applicable to work on the surface of the conductive magnetic material. As shown in Figure 9, the Danish company CLIIN has also developed a magnetic adsorption crawler CHR, which is specially used for cleaning the hold of bulk carriers. The size of 900 × 510 × 440 mm, self-weight 54 kg, load capacity of 50 kg, moving speed of 40 mm / s.[21] Zhejiang University, College of Oceanography, Professor Zhu Shiqiang team developed a magnetic wheel climbing wall robot for ship surface rust removal cleaning, as shown in Figure 10, the robot has a set of magnetic adsorption crawling wheels on each side of the wall in order to achieve the wall adsorption and walking; the middle of the rotating nozzle rod, The center is a cleaning and recycling assembly composed of a rotating spray bar, a vacuum cleaning disk, and a brush; the rear end has two driven wheels composed of universal wheels, and a magnetic adsorption assembly is installed between the two driven wheels to prevent tipping. The paint removal efficiency of this robot can reach 40m2 / h.[22] The above two robots have high reliability of adsorption, high speed, strong payload, but the ability to cross the obstacles in general, poor applicability.

Fig. 9. CHR wall climbing robot

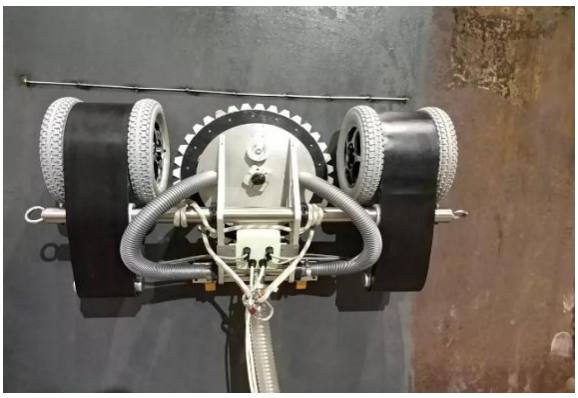

Fig. 10. Wall Climbing Robot with Magnetic Wheels

2.2.2 NEGATIVE PRESSURE ADSORPTION WALL CLIMBING ROBOT

Negative pressure adsorption refers to the creation of a pressure environment lower than the outside atmosphere in the sealed cavity, relying on the pressure generated by the pressure difference between the inside and outside of the sealed cavity to make the robot adsorption on the wall surface. Negative pressure adsorption is not affected by the material of the wall surface, can produce a large adsorption force, is the most commonly used in the non-conductive wall surface of a kind of adsorption technology. Negative pressure is generated by vacuum pumps, venturi, centrifugal fans and other means.

Seoul National University has developed a crawler-suction cup wall-climbing robot as shown in Figure 11, which uses crawler movement and vacuum suction cups for adsorption. Each track of the wall climbing robot is equipped with 12 small vacuum suction cups, and the suction state of each suction cup is controlled by a solenoid valve. The overall weight of the wall-crawling robot is 5.6 kg, and the maximum moving speed is 1.8 m/min.[23] The Rise-Rover developed by the City University of New York has three independent negative pressure chambers installed inside each crawler, and the negative pressure chambers are generated by impellers or centrifugal fans to generate negative pressure, which are connected to the suction cups in the wall section of the crawler, so that the crawler can be adsorbed on the wall surface while it is in motion, as shown in Figure 12. The track is soft and thick enough to accommodate walls with some degree of cracks and grooves. However, due to the small effective adsorption volume of the negative pressure chamber, the robot load weight is relatively small; the special structure of the track makes it difficult to design and process.Rise-Rover can work effectively on vertical surfaces with small gaps or grooves.Rise-Rover has a deadweight of 11kg, and it can carry a weight of 7.26kg on a vertical wall at a travel speed of 30 meters/minute.[24-25] The above two robots have high adsorption reliability, slow movement speed, average payload, and average obstacle-crossing ability for different types of work surfaces.

Fig. 11. Crawler suction cup wall climbing robot

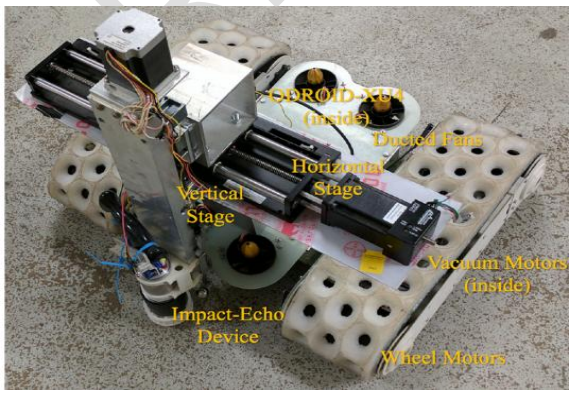

Fig. 12. Rise-Rover wall climbing robot

2.2.3 BIONIC ADSORPTION WALL CLIMBING ROBOT

Bionic adsorption can be further categorized into electrostatic, chemical and mechanical adsorption. This kind of adsorption has low noise and wide application. Bionic adsorption wall climbing robot small size, low energy consumption, can be in the city high-rise buildings, bridges and other concrete building wall climbing. Stanford University in the United States to imitate the gecko's adsorption and movement mechanism developed Stickybot robot, as shown in Figure 13. Stickybot's foot using dry adsorption material, when the foot to the wall and the pressure, the use of the foot and the wall and the van der Waals force between the adsorption of their own in the wall and the other way around, the foot can be detached from the wall. sfickybot light weight, suitable for climbing glass, plastics and other materials. Sfickybot is lightweight and suitable for climbing glass, plastic, tiles and other wall surfaces.[26] At the same time, they also simulate the characteristics of animal climbing limb movement, developed a quadrupedal robot LEMURsIIb, as shown in Figure 14, the robot can climb vertically on complex rock surfaces, able to adapt to the complex environment of the multi-planar, with more functions, such as assembling, checking, maintaining, transporting, intervening, and so on, the movement is flexible and simple to operate.[27] The above two robots have general adsorption reliability, faster movement speed, poor payload, strong obstacle-crossing ability and adaptability.

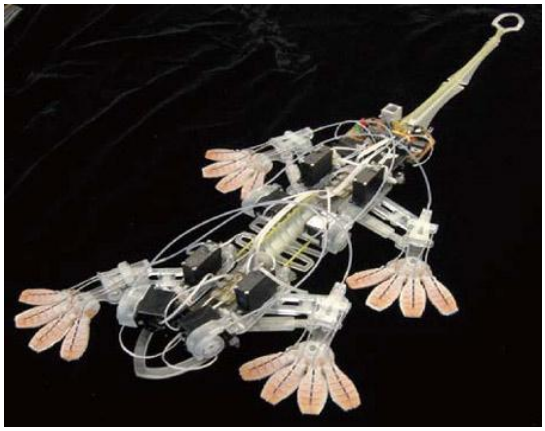

Fig. 13. Stickybot wall climbing robot

Fig. 14. LEMURIIb wall climbing robot

3.1 ANALYSIS OF KEY TECHNOLOGIES FOR WALL-CLIMBING ROBOTS

3.1.1 ADSORPTION TECHNOLOGY

Wall climbing robot can rely on the adsorption mechanism on the surface of the force generated by the robot to overcome the gravity, so that it does not produce sliding. At present, the adsorption method mainly has vacuum negative pressure adsorption, magnetic adsorption and special adsorption and other ways, but in order to meet the structure of lightweight and can produce enough adsorption force is still difficult to meet, such as vacuum negative pressure adsorption requirements to be adsorbed on the surface of the surface is smooth and clean, and the surface of the adsorption can not produce air leakage, magnetic adsorption requirements to be adsorbed on the surface of the magnetism conductive, special adsorption requirements for the surface is clean and can not be dust and so on.

3.1.2 MOBILE MECHANISMS AND MOTION CONTROL SYSTEMS

As mentioned earlier, the mobile structures of wall-climbing robots are usually wheeled, footed, tracked, and hybrid, among which, footed and tracked are more widely used. Wall-climbing robots require high obstacle-crossing capability, which is also an extremely difficult problem for engineering applications. When there are bumps and grooves on the wall, the robot is required to be able to pass through them smoothly, so the wall climbing robot has to meet the adequate obstacle-crossing ability. For different mobile mechanisms, the foot-type robot has the best obstacle-crossing ability, which is due to the fact that when the robot encounters an obstacle, it can be controlled to lift each leg of the robot to cross the obstacle, and its ability to pass is stronger. As the movement of the wall climbing robot is to ensure reliable adsorption on the wall under the premise of the flexible mobility of the strand away, and the wall climbing robot working on the wall of the particularity of the mobile and adsorption mechanism there is a coupling problem, which causes difficulties in the motion control of the robot. Such as foot-type suction cup wall climbing robot structure, when the leg movement, due to a suction cup at the end of each leg, each move a leg, the action process is "to adsorption - lifting the leg - leg forward - drop leg - adsorption ", this series of actions in the wall climbing robot mobile mechanism and adsorption mechanism requires coordinated action to ensure its flexible movement in the wall, if this series of coupled movement control is not good, will lead to the instability of the wall climbing robot movement.

3.1.3 ENERGY SUPPLY AND DRIVE PROBLEMS FOR WALL-CRAWLING ROBOTS

Power supply for wall climbing robots is another key issue for robots, especially if the robot has to be as light as possible. The energy supply of the robot can be supplied by cables, by piping, or by its own batteries or gas cylinders. The drive of the robot is based on the way of energy supply, mainly electric, pneumatic and so on. In the design of wall-climbing robots, it is important to use actuators or drive sources with as high a torque-to-mass ratio as possible. If the use of self-contained energy, the energy-to-weight ratio is required to be as high as possible, such as the use of electric drive, the energy can be used nickel-metal hydride batteries, lithium batteries, fuel cells and so on. Some wall-climbing robots can also use miniature internal combustion engines as the energy supply, such as gasoline engines.

4.1 THE FUTURE OF WALL-CLIMBING ROBOTS

Combined with the above research status and adsorption technology analysis, it can be seen that the wall climbing robot after decades of vigorous development, although some scientific research results, but most of the universities and institutions of the research is still in the laboratory stage, and has not been applied to the actual project, there is still a great distance from industrialization. Adsorption technology, mobile technology and control technology is still to be developed, so the current wall climbing robot from the large-scale application there is still a gap. With the overcoming of

these problems, the future engineering applications of wall climbing robots will be more in-depth and extensive. The future wall climbing srobot focuses on the development direction of intelligent, lightweight, generalized and so on.[28-30]

5.1 CONCLUSION

After years of development, the field of wall climbing robots has achieved quite fruitful research results, but only a very small number of wall climbing robots have been practically applied in some fields, with the development of new technologies and the increase in demand, the design of wall climbing robots has also put forward newer and higher requirements. In this paper, from the perspective of wall climbing robot's moving mode and adsorption mode, it is classified and reviewed, and the characteristics of several common wall climbing robots are analyzed and compared. Finally, it is proposed that the research of wall-climbing robots will develop in the direction of intelligentization, lightweight, cable-free and generalization, and will be very useful in the future in the fields of ships, wind power, petrochemical industry, investigation and disaster relief, and so on.

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