Journal of Materials, Processing and Design (2024)
Clausius Scientific Press, Canada
DOI: 10.23977/jmpd.2024.080216
ISSN 2516-0923 Vol. 8 Num. 2

Design and Simulation Analysis of the Motion Mechanism of Building Glass Curtain Wall Cleaning Machines

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Keywords: Building glass curtain walls, Cleaning machines, Crawling mechanisms, Cleaning mechanisms, Three-dimensional motion simulation, Solid Works

Abstract: In response to the obstacle-crossing requirements for glass curtain wall cleaning operations, this paper proposes a symmetrical motion mechanism that can vertically adsorb to the wall surface pneumatically. It adopts the way of the robot lifting its "feet" to walk. The crawling mechanism and cleaning mechanism of the building glass curtain wall cleaning machine are designed. The motion characteristics of the cleaning machine's crawling mechanism walking freely and stably on the glass curtain wall under the action of gravity are analyzed, and the working principle of the automatic glass curtain wall cleaning operation is expounded. The virtual model of the cleaning machine is established through the three-dimensional design software SolidWorks. Through motion simulation analysis, appropriate motion trajectories are found, structural parameters are optimized, and efficient cleaning operations within the shortest time are achieved, effectively solving the problems such as poor obstacle-crossing ability and inconvenient manipulation of the current building curtain wall cleaning machines. This design has important theoretical guiding significance and application value for the research and development of glass curtain wall cleaning machines.

1. Introduction

In today's society, most high-rise buildings adopt glass curtain walls in order to combine aesthetics and brightness. However, glass curtain walls are easily soiled as they are exposed outdoors for a long time. Therefore, the cleaning of dirty glass curtain walls is a very important and necessary operation.

According to investigations, at present, manual cleaning operations are basically adopted both at home and abroad. This method relies on lifting platforms or hanging ropes for people to clean the glass curtain walls. This operation mode has a high risk factor, low efficiency, high cost, and the effect is far from satisfactory. Moreover, the sewage from manual cleaning drifts everywhere, causing secondary pollution. Therefore, researching and developing glass curtain wall cleaning machines to replace manual operations will greatly reduce the cleaning costs of high-rise buildings, improve labor productivity, and have considerable social and economic significance as well as broad application prospects.

Related foreign research includes: In 1966, Professor Nishikyo from the Faculty of Engineering at Osaka Prefecture University in Japan developed the first robot that could move on vertical walls. It moved on the wall by using the low-pressure effect on the intake side of an electric fan as the adsorption force [1]. In 1990, the Russian Academy of Mechanical Sciences successfully developed a single-suction-cup wall-climbing robot for cleaning operations. It carried out cleaning operations by moving with the suction force of the suction cups of two pairs of relatively independent wheels [2]. In 2005, the United States researched a wall-climbing robot that walked in an insect-like peristaltic manner [3]. In 2012, the Universiti Teknologi Malaysia studied a wall-climbing robot that moved by relying on piston ropes [4]. In 2013, Germany developed a new type of wall-climbing robot that walked by relying on hot-melt bonding [5]. Related domestic research includes: Since 1988, with the support of the national "863" program, Harbin Institute of Technology has developed two series of robots using magnetic adsorption and vacuum adsorption [6-7]. In 2001, Beihang University designed the SKY-III robot [8]. In 2011, Southwest Jiaotong University developed a vertical glass curtain wall cleaning robot with a multi-suction-cup combined walking mode [9]. Hefei General Machinery Research Institute developed a wall-climbing robot that climbed by relying on magnetic adsorption force [10]. In 2013, Nanjing University of Aeronautics and Astronautics developed a wall-climbing robot that walked in a gecko-like crawling manner [11]. Whether the above robots are driven by wheels or move by the peristaltic movement of the robot body, they all have problems such as poor obstacle-crossing ability, low efficiency, and inconvenient operation.

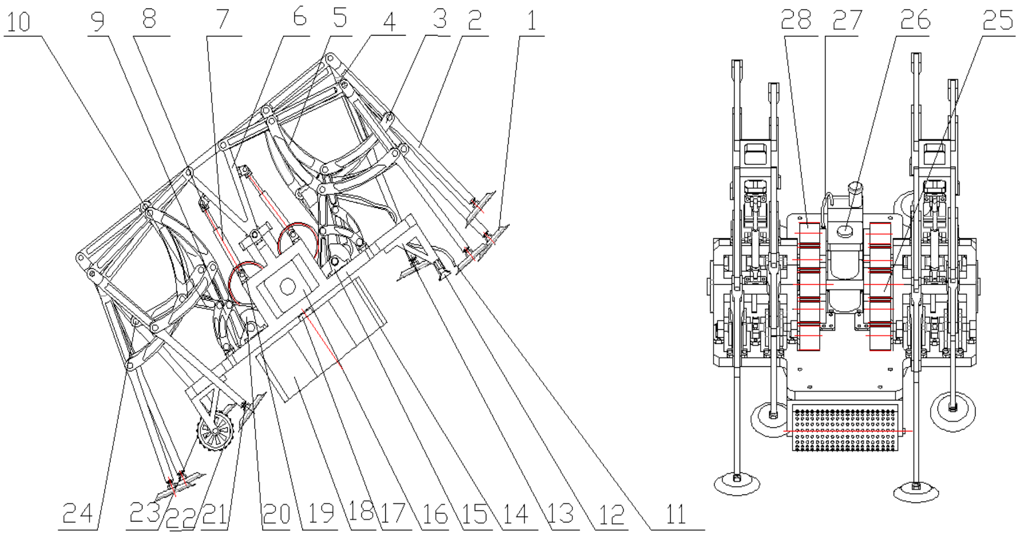
Aiming at the obstacle-crossing requirements of glass curtain wall cleaning machines and with the purpose of realizing the automatic cleaning of glass curtain walls, this paper studies and designs a symmetrical mechanical crawling motion mechanism and a cleaning mechanism that can rely on pneumatic vertical adsorption on the wall surface to solve the above problems.

2. Design of the Motion Mechanism of the Building Glass Curtain Wall Cleaning Machine

2.1. Overall Scheme Design and Working Principle of the Cleaning Machine

The overall design scheme of the cleaning machine is shown in Figure 1, which mainly consists of two parts: the crawling mechanism and the cleaning mechanism. The crawling mechanism mainly consists of a symmetrical link curve mechanism, an amplifying mechanism and a shock-absorbing tripod. The cleaning mechanism is composed of a horizontal drum, a vertical cleaning cylinder and a rear cleaning treatment scraper, etc.

Its working principle is as follows: Driven by the electric motor, the crawling mechanism converts the rotational power of the electric motor into the swinging movement of the machine feet through the symmetrical four-bar linkage curve mechanism. Then, the vacuum suction cups at the ends of the feet, in cooperation with the movement of the machine feet through the air pressure control system, enable the cleaning machine to crawl on the glass curtain wall. The cleaning work is completed by the cleaning mechanism composed of the horizontal drum, the cleaning vertical cylinder and the rear cleaning treatment scraper.



Notes: 1. Pneumatic suction cup 2. Telescopic structural rod (1) 3. Telescopic structural rod (2) 4. Telescopic structural rod (3) 5. Telescopic structural rod (4) 6. Balanced shock-absorbing tripod 7. Shock-absorbing piston cylinder 8. Shock-absorbing piston rod 9. Connecting frame of symmetrical curve mechanism 10. Connecting rod of symmetrical curve mechanism 11. Dirty matter collection pipeline 12. Rear cleaning treatment scraper 13. Machine body fixed tripod 14. Machine main body 15. Crankshaft support seat 16. Electric motor (1) 17. Rotary shaft of the cleaning vertical cylinder 18. Cleaning vertical cylinder 19. Shock-absorbing piston support 20. Crankshaft 21. Hinge ball 22. Horizontal drum 23. Drum sleeve 24. Pin 25. Power output driving gear 26. Electric motor (2) 27. Oil pipe 28. Transmission gear

Figure 1: Overall Scheme of the Cleaning Machine

2.2. Design of the Crawling Mechanism

(1) Design of the Symmetrical Four-bar Linkage Curve Mechanism of the Crawling Mechanism

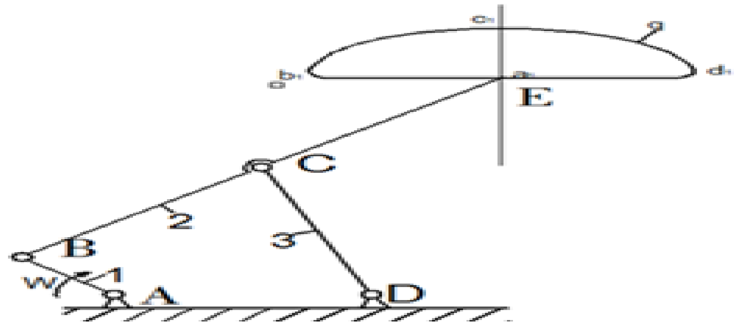


Figure 2: Symmetrical Linkage Curve Mechanism of the Crawling Mechanism

Firstly, it is necessary to analyze and plan the walking gait path and trajectory of the machine [12-14]. This design proposes a new type of curved trajectory. As shown in Figure 2, a four-bar linkage mechanism with hinges is adopted, which consists of bars AB, BC, CD and the frame AD. The working principle is as follows: When the four-bar linkage mechanism with hinges satisfies the length relationship that CD = BC = CE, that is, CD = 2BE, when the driving component 1 rotates for one cycle, point E on component 2 will describe a trajectory q to obtain a1 - b1 - c1 - d1 - a1, as shown in Figure 2. It is composed of an arc on the upper side and an approximate straight line on the lower side. The straight line part is taken as the motion trajectory of the walking part. Meanwhile, the straight line segment is also the working section where the machine completes the cleaning work, which is particularly important. The straight line trajectory ensures that the machine body always maintains a fixed distance from the wall surface during work. Since the cleaning mechanism is fixed on the machine body, this also ensures that the entire cleaning mechanism always maintains a fixed distance from the wall surface, so that the cleaning work can be completed. And the curved part on the upper side is taken as the motion trajectory of lifting the leg, which well meets the requirements for the robot to walk on the wall surface and complete the cleaning work.

(2) Design of the Amplifying Mechanism of the Crawling Mechanism

Using only the symmetrical linkage curve structure to overcome obstacles is limited. Moreover, such a structure is rather large, uneconomical and has poor effects. Therefore, an amplifying mechanism is designed to enlarge the step length to meet the requirements. The working principle of the amplifying mechanism is as follows: As shown in Figure 3, ABCD is a parallelogram, and AC / BE = OA / OB = a constant (amplification ratio). If point O is fixed, points C and E will respectively draw similar trajectories amplified by this amplification ratio as shown in the figure. According to the actual inspection of the size of obstacles on the glass curtain wall and in combination with simulated and optimized parameters, the designed required amplification ratio is 2.5:1.

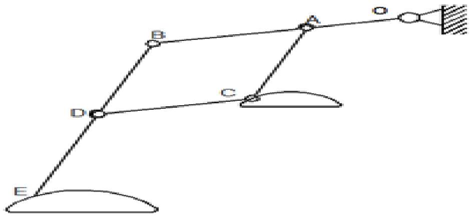


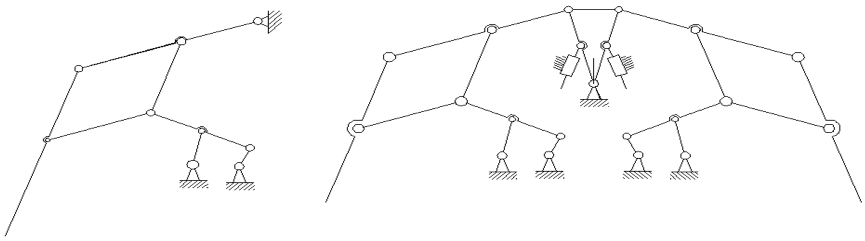
Figure 3: Amplifying Mechanism of the Crawling Mechanism

(3) Design of the Shock Absorption Mechanism of the Crawling Mechanism

In order to meet the obstacle-crossing requirements and resist the risk of vibration, a shock absorption mechanism is designed. The crawling mechanism of the cleaning machine is a mechanism with one redundant degree of freedom, and its function is to absorb and dampen shocks. The mechanism consists of a balanced shock-absorbing tripod and shock-absorbing pistons.

(4) Combined Structure

The combination of the symmetrical linkage curve mechanism and the amplifying structure forms a single foot of the machine, as shown in Figure 4(1). Combining the single foot with the shock-absorbing mechanism forms one side of the machine, as shown in Figure 4(2).



(1) Combination of a Single Foot of the Machine (2) Combination of One Side of the Machine

Figure 4: Combined Diagram of the Crawling Mechanism

(5) Transmission System of the Crawling Mechanism

A reduction motor is directly adopted to achieve the purpose of speed reduction. According to the actual requirements, two crawling mechanism motors are used, with one on each side and symmetrically distributed to achieve a stable and balanced effect. For the intermediate transmission, ten gears with the same parameters are employed, with five symmetrically distributed on each side and the driving gear in the middle. The transmission is shown in Figure 5, and such a transmission mechanism is quite stable.

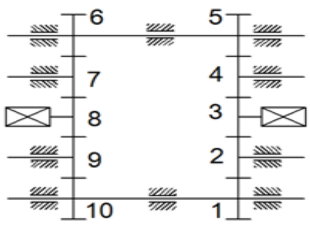


Figure 5: Transmission System of the Crawling Mechanism

2.3. Design of the Cleaning Mechanism

(1) Horizontal Drum

The horizontal drum consists of rollers, a plastic layer and cleaning balls. When the cleaning machine moves forward, it drives the rollers to move forward, and the cleaning balls rub against the wall to clean the wall surface [15]. There are two main purposes for the design of the drum. One is to wet the wall surface; the other is to initially scrub the wall surface.

(2) Cleaning Vertical Cylinder

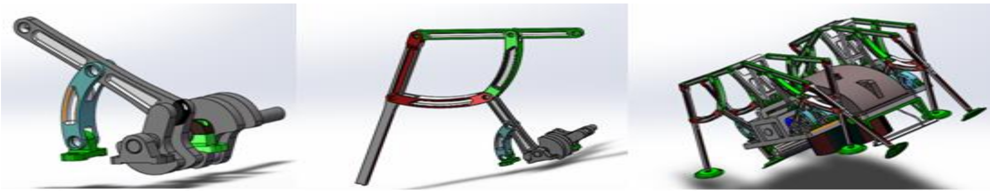
It is driven to rotate by an electric motor, and the friction layer on its surface rubs against the wall surface, so as to achieve the purpose of cleaning the wall surface.

(3) Rear Cleaning Treatment Scraper

After the wall surface has been cleaned, there will always be some cleaned dirt left, which can no longer adhere firmly to the wall surface. At this time, the scraper comes into play. Its main function is to continue to scrape and clean the cleaned glass.

3. Three-dimensional Motion Simulation and Analysis of the Building Glass Curtain Wall Cleaning Machine Based on SolidWorks

3.1. Physical Modeling



(1) Symmetrical Linkage Curve Mechanism (2) Single-foot Combined Mechanism (3) Overall Combined Mechanism

Figure 6: Physical Modeling

Since each of the four corners of the machine requires two feet working together to maintain a balanced adsorption on the wall surface while walking, that is, one foot touches the wall while the other is lifted up, meeting the requirement of a 180-degree plane. Therefore, the connecting rod AC is designed as a crankshaft to complete the coordinated movement. The physical model in SolidWorks is shown in the model diagram of Figure 6(1). The combination of the symmetrical linkage curve mechanism and the amplifying mechanism forms the single-foot combined mechanism of the crawling mechanism, as shown in the model diagram of Figure 6(2). To make the whole machine balanced, the machine feet should be symmetrically distributed and perform alternate crawling. So, two feet must be designed at each corner, and then the cleaning mechanism is assembled. In this way, the entire crawling mechanism becomes a symmetrical and balanced mechanism with eight feet, as shown in Figure 6(3).

3.2. Three-dimensional Motion Simulation and Analysis

(1) Motion Simulation and Analysis of the Symmetrical Linkage Curve Mechanism

After the model is assembled in the SolidWorks software, the rotation of the crankshaft around the shaft seat is used to simulate the rotary motor. The simulated trajectory is generated by using the motion analysis function of SolidWorks, as shown in Figure 7. Through the animation display, the formation process of the symmetrical linkage curve can be clearly seen.

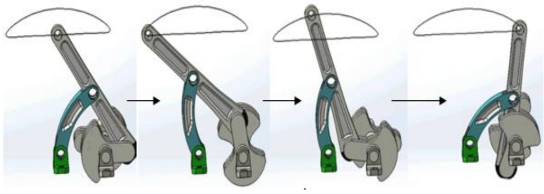


Figure 7: Motion Simulation of the Symmetrical Linkage Curve Mechanism

The specific dimensions obtained by amplifying the output trajectory of the symmetrical linkage curve by 2.5 times through the amplifying mechanism are shown in Figure 8. The analysis diagram shows that AB = BC = 70 mm. Then, as the main mechanism of the crawling mechanism, the stride AC of the symmetrical linkage curve is 140 mm. BD = 27 mm, that is, the obstacle that the symmetrical linkage curve can cross is 27 mm.

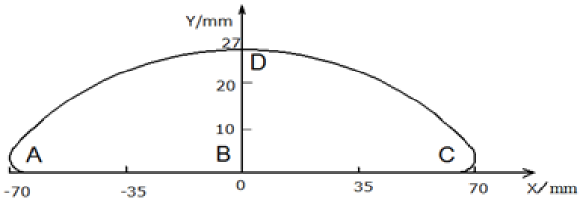


Figure 8: Motion Trajectory of the Symmetrical Linkage Curve Mechanism

Motion Law: Take point B on the output curve trajectory as the starting point of the crankshaft rotation (i.e., 0 degrees). When the crankshaft rotates clockwise, the trajectory law is approximately as follows: When the crankshaft rotates 90 degrees, the trajectory is output to point C; when it rotates 180 degrees, the output trajectory reaches point D; when it rotates 270 degrees, the output trajectory reaches point A; when it rotates 360 degrees, the output trajectory returns to the starting point B, thus completing a cycle of motion and trajectory output.

(2) Motion Simulation and Analysis of the Whole Machine

The building glass curtain wall cleaning machine uses the SolidWorks software to assemble all the parts and components, as shown in Figure 9. It is the motion simulation process of the whole machine for one cycle. With the two symmetrically distributed electric motors as motors, the figure can clearly display the motion state of the whole machine, achieving the simulation of the working situation on the glass.

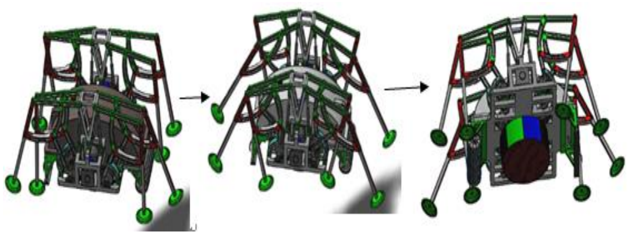


Figure 9: Overall Machine Motion Simulation

To analyze the motion state of the moving machine, it is sufficient to analyze only a single foot. The stride of the whole machine is 2.5 times that of AC, which is 140 mm, and the obstacle-crossing height is 2.5 times that of BD, which is 67.5 mm.

In the single-foot combined mechanism, as shown in the single-foot structure diagram in Figure

4, the movement of point g at the end of the amplifying mechanism: Through the motion analysis of SolidWorks [16-20], with the set motor output rotational speed of 6 r/min, the motion law within one cycle of the trajectory curve can be obtained. (Note: The black represents the horizontal component, that is, the X component, the blue represents the vertical component, that is, the Y component, and the vertical red line indicates the time point when the trajectory point is at point B in Figure 8.)

The motion time of the straight line segment accounts for approximately T/2, and the motion time of the arc segment is approximately T/2. The entire motion law is a periodic motion with a period of 10 s. The horizontal trajectory (the black line) is similar to the law of the sine function curve, and the curve law is symmetrically distributed. Therefore, the maximum distance that the trajectory can reach on both sides with respect to the X-axis is 70, that is, the stride of the machine within one cycle is 140 mm. For the vertical component (the blue line), it can be seen from the figure that the highest point is 26 and the lowest point is -1. Then the height span for the machine to overcome obstacles is 27 mm.

For the horizontal component (the black line), the velocity is relatively stable between the 3rd second and the 8th second, and the stable velocity is 25 mm/s. This segment is the straight line segment, that is, the working segment of the machine. So, the stable velocity exactly meets the actual requirements. For the arc segment, as can be seen from the figure, it first accelerates to the maximum velocity, then decelerates from 25 mm/s to 0 mm/s, and then accelerates in the reverse direction to the maximum velocity value of 91 mm/s. For the vertical velocity component (the blue line), the velocity is 0 mm/s during the straight line segment. It does not start to accelerate until the arc segment. When it accelerates to the maximum velocity of 22 mm/s, it begins to decelerate, and after decelerating to 0 mm/s, it accelerates in the reverse direction, then reaches the maximum velocity value of 23 mm/s, and then returns to the horizontal straight line segment where the velocity recovers to 0 mm/s.

The horizontal acceleration (the black line) is initially 0 mm/s^2, which means that the straight line segment is almost in uniform motion. And the working segment happens to be the straight line segment, which well meets the requirement for the stability of the machine during the cleaning work. In the arc segment, it is a variable acceleration motion with the acceleration gradually increasing, and the maximum acceleration is 17 mm/s^2. After that, the speed decreases uniformly to 0 and then increases in the reverse direction to 17 mm/s^2. The arc segment is the non-working segment when the foot is lifted, so a certain range of flexible impact during the walking of this machine is allowed and will not affect the operation of the machine. The vertical acceleration has relatively little impact on the operation of the machine.

4. Conclusions

Through the comprehensive motion simulation, motion analysis by SolidWorks and kinematic analysis of the building glass curtain wall cleaning machine, the following conclusions are obtained:

1) The building glass curtain wall cleaning machine with the walking mode of lifting feet has better obstacle-crossing capabilities, filling the deficiencies of the traditional creeping walking mode such as poor obstacle-crossing ability, low working efficiency and inconvenient operation.

Meanwhile, it can also meet the requirements for wall surface cleaning, thus proposing a new solution for glass curtain wall cleaning.

2) Through the amplifying mechanism and the symmetrical distribution of the mechanism, the structural distribution of the whole machine can be optimized, reducing the relative weight of the overall machine. This paper proposes a new method for mechanism optimization, especially the proposal of the amplifying mechanism.

3) The building glass cleaning machine has excellent motion performance. The crawling mode with the symmetrical linkage curve trajectory makes its speed and acceleration well meet the requirement for the motion stability of the symmetrical machine when walking on the vertical glass curtain wall, enabling the machine to have high working efficiency and feasibility.

Acknowledgements

1) Major Project of Basic Science (Natural Science) Research in Colleges and Universities in Jiangsu Province (23KJA460003),

2) Teaching Reform Project of Degree and Postgraduate Education in Jiangsu Province (JGKT24_C084)

References

[1] Zhang Xiaosong. Research on Wheeled Wall-Climbing Robot with Suspended Magnetic Adsorption [D]. Harbin: Mechatronics Engineering, Harbin Institute of Technology, 2012.

[2] Yi Z Y, Gong Y J, Wang Z W, et al. Development of a wall climbing robot for ship rust removal[C]//IEEE International Conference on Mechatronics and Automation. Piscataway, USA: IEEE Computer Society, 2009: 4610-4615.

[3] Nkgatho Sylvester Tlale, Glen Bright, W. L. Xu. Distributed control of hexapod wall climbingrobot implementing Controller Area Network (CAN)[J]. IJISTA, 2005, Vol.1.

[4] Y.C. Koo, Elmi A.B., Wan Amir Fuad Wajdi. Piston mechanism based rope climbing robot[J].Procedia Engineering,2012,41(2):2-7.

[5] Marc Osswald, Fumiya Iida. Design and control of a climbing robot based on hot melt adhesion[J]. journal homepage,2013,28(5):3-8.

[6] Zhao Yanzheng, Men Guangliang, Feng Hai, Wang Yan. Research on Attitude Control of Omnidirectional Wall-Moving Robot [J]. Journal of Harbin Institute of Technology, 1997, 29(6): 2-3.

[7] Shao Hao, Zhao Yanzheng, et al. Wall-Climbing Robot System for Glass Curtain Wall Cleaning Operations [J]. Manufacturing Automation, 2002, 22(2): 6-9.

[8] Qian Zhiyuan, Liu Renqiang, Zhao Yanzheng, et al. A Wall-Traction Mobile Glass Curtain Wall Cleaning Robot [J]. Journal of Shanghai Jiaotong University, 2006, 40(11): 18-21.

[9] Xu Dong, Yang Mingkai, et al. Design of Vertical Glass Curtain Wall Cleaning Robot [J]. China Science and Technology Information, 2011(8): 5-8.

[10] Xue Shengxiong, Ren Qile, et al. Development of Magnetic Gap Wall-Climbing Robot [J]. Journal of Mechanical Engineering, 2011, 47(11): 2-4.

[11] Zhang Hao, et al. A Lateral Ground-Wall Transition Method and Gait of Gecko-like Robot [J]. China Mechanical Engineering, 2013, 24(5): 2-5.

[12] Yue Ronggang, Wang Shaoping. Path Planning of Wall-Climbing Robot Based on Mixed Integer Linear Programming [J]. Journal of Beihang University, 2013, 39(6): 2-5.

[13] Tian Lantu. Research on Technology and System of Wall-Climbing Robot for Oil Tank Detection [D]. Tsinghua

University, 2004.
[14] Ji Guozhao, et al. Research and Development of Vacuum Suction Cup Wall-Climbing Cleaning Robot [J]. Mechanical Research & Application, 2009: 2-6.
[15] Zhou Yanwu, Zong Guanghua. Intelligent Technology of Cleanbot-I Window Cleaning Robot [J]. Robot, 2002, 24(1): 6-11.
[16] Liu Aihua, Wang Hongguang, et al. Mechanism Modeling and Analysis of a Wheel-Legged Composite Wall-Climbing Robot [J]. Robot, 2008, 30(6): 487-489.
[17] Wang Binrui, Feng Weibo. Design and Stability Analysis of Biped Wall-Climbing Robot with Three Degrees of Freedom on Curved Surface [J]. Robot, 2014, 36(3): 1-4.
[18] Fu Yili, Li Zhihai. Research Progress of Wall-Climbing Robots [J]. Journal of Mechanical Design, 2008, 25(4): 1-3.
[19] Mao Zhiwei, et al. Study on Mechanical Properties of Suction Cups of Biped Mobile Wall-Climbing Robot [J]. Machinery Design & Manufacture, 2010(8): 159-161.
[20] Jiang Jian, Jing Xuedong. Research on Ground-Wall Transition of a Soft Robot [J]. Journal of Shanghai Institute of Technology, 2014, 14(1): 2-5.