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Original Article

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A gecko-inspired wall-climbing robot based on vibration suction mechanism

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Abstract

A prototype of gecko-inspired wall-climbing robot based on vibration suction mechanism is proposed. The robot adheres to the wall surface based on a novel negative pressure technology named as vibration suction. According to the theory of vibration suction, the vibration suction module is designed as the foot of the wall-climbing robot. In addition, the tripod gait of geckos is taken into account in the motion planning of the robot. By combining the unique properties of vibration suction mechanism and the tripod gait of the geckos, several advantages including stable motion, certain load capacity, anti-overturning ability, and good suction force to the wall surfaces are obtained. The climbing ability is verified by the experiment on the surface of the glass, which manifests that the robot can climb vertically at the highest speed of 13.75mm/s with a spot turning at the single maximum turning angle of 20°. For potential applications of this proposed climbing robot in some fields include repair, construction, cleaning, and exploration.

Keywords

Wall-climbing robot, gecko-inspired, negative pressure, vibration suction mechanism, tripod gait

1. Introduction

There exist a variety of tasks that need to be handled on vertical wall surfaces especially for some hazardous and specialized work, such as cleaning the glass of a skyscraper,[1,2] inspection of ship hulls and nuclear sealed tanks,[3,4] scouting in the field of counter-terrorism[5] and so on. In order to relive humans from these dangerous work, wall-climbing robots are often used. In order to make the wall-climbing robot move stably on the wall, two basic factors must be taken into account when a wall-climbing robot is built. One is suction method, which enables the robot to be adhered tightly to the wall without slipping; the other relating to the practicality is locomotive mechanism, as it will determine how fast the robot moves for different situations.

As for the suction technology, they can be commonly classified into four categories: magnetic adhesion, van der Waals force, electrostatic adhesion and negative pressure. Magnetic adhesion[6,7,] can provide a large suction force and its application is very extensive. However, it can only be used on the ferromagnetic surface. Recently, the van der Waals force[8,9,10] inspired by geckos has become a research hotspot, but it is usually used in high quality conditions since it demands high degrees of surface finish and cleanness. Electrostatic adhesion method[11,12] requires relatively low conditions for wall surface, which can be used on various wall surfaces. However, the adhesion force of this method is quite weak. It is noted that the negative pressure[13,14] technology is one of the widely-applied and mature suction methods used on the wall-climbing robot. However, climbing robots using traditional negative pressure usually need to carry a bulky pump or fan, which will lead to a complex structure, low speed and load capacity. Unlike traditional negative pressure method, the vibration suction [15,16] does not require any extra equipment or external tubes, which uses the vibration of its own suction cup to generate a negative pressure and thus firmly adheres to the wall. Therefore, it has a lot of advantages including low energy consumption, low noise, low mass, and reliable suction.

Locomotive mechanism is another vital factor when a wall-climbing robot is designed, which can be mainly divided into types of wheel-driven, tracked, and legged. Existing research results indicate that the wheel-driven wall-climbing robot[17,18] has the advantages of large moving speed, flexible movement and simple control. However, the obstacle-tolerant ability is not good so that they can only move on the smooth wall. The tracked type wall-climbing robot[19,20] takes the advantages of large driving force and strong maneuver ability. However, the robots have a poor ability to cross obstacles and their weight are usually large. Meanwhile, it can only be used in some occasions where the robot is not required to be too bulky. Wall-climbing robots using legged locomotion have different types from two up to eight legs for different uses.[21-24] Theoretically, the legs can be moved in any direction with a certain number of degrees of freedom, so that they can move over rough surfaces or cracks, and easily cope with obstacles. In addition, a better supporting force will be obtained with the growing number of legs of the robot, which can make the wall-climbing robot move stably and increase the capacity of the payload. However, with the number of legs increasing, a more complicated control system needs to be adopted. Inspired by climbing animals[25], especially geckos, wall-climbing robots can be envisioned and put into use. As we know, the gecko is arguably the most flexible and smooth surface climber of climbing animals. They can run on dry and wet surfaces in any direction, with varying degrees of roughness and all kinds of materials. The most representative wall-climbing robot named Stickybot[26], can climb on smooth walls but without self-cleaning of the adhesive materials, leading to only a few adhesion times. Although the appearance of the robot is close to the real gecko, each leg of this robot only has two degree of freedoms and the gait planning has no relevance with the movement of the real gecko. In addition, a series of Micro Tugs robots[27], which were developed by Stanford University, can carry loads 100 times heavier than itself. However, this robot has a slow response time, as it is actuated by externally powered shape memory alloy. In this paper, we design a wall-climbing robot based on motion modes of geckos and a vibration suction mechanism, which has 5 degree of freedoms and can achieve multiple adhesion times.

The vibration suction mentioned above is a reliable suction technique with reliable suction force. Therefore, this paper proposes to combine the vibration suction mechanism with the gait of geckos to design a wall-climbing robot. The content of this paper is as follows: in the section, the prototype and working principle of a gecko-inspired wall-climbing robot based on vibration suction mechanism are described. Furthermore, the vibration process and pressure change of a suction cup in one cycle are analyzed and the mathematical model of the single suction cup is established, then the related experiments are finished to verify the above analytical accuracy. Next, the structures of the robot and the vibration suction module are introduced, meanwhile, the force analysis is discussed. Finally, tests of the robot are carried out, where the test results demonstrate that the robot can climb vertically on the high-glass surface with certain obstacle crossing and turning ability. The remaining part followed by the conclusion, which presents a summary and suggests the future work.

2. Theoretical analysis of vibration suction

(1) The vibration of a suction cup

Vibration suction[28] is primarily put forward by Robot Research Institute of Beijing University of Aeronautics &Astronautics, which is inspired from the hook with a silicone suction cup which is used to suspend something in our daily life. As we know, a suction cup can adhere to the wall surface for a period of time if we press it onto a clean and smooth wall surface due to the pressure difference between the inner and outer space of the suction cup. However, as time goes by, the air outside of the suction cup will penetrate into the inside of the cup slowly until the cup slides or falls due to the decrease of the pressure difference. Fortunately, the suction cup can adhere to the wall surface again if we pick it up and press it onto the wall surface again for another period of time. Therefore, we can imagine and design a vibrating mechanism which can produce a continuous cyclic push-down and pull-up movement of the suction cup, so that the suction cup can adhere to the wall surface steadily for a long time. [Insert Figure 1.]

When a suction cup vibrates against the wall, the change of airflow is shown in Figure 1, which shows the complete vibration process of a suction cup for one cycle. Figure 1(a) shows that the suction cup is in the initial position without any external force, where the internal pressure P_i is equal to external pressure P_o, namely $P_i = P_o$. In Figure 1(b), the suction cup is pulled up, and enlargement of the internal space of the suction cup enables $P_i < P_o$. This allows the air outside flow into the suction cup through gaps, however, the rate of increasing pressure caused by air leakage is slower than the decreasing pressure caused by the expansion of internal space. Hence, the internal pressure P_i continues to decrease until it reaches the highest position. In Figure 1(c), as the suction cup is pushed down, the air continues to enter the cup and P_i will increase gradually. When $P_i > P_o$, the air begins to flow out of the inside the suction cup, resulting in the rate of increasing P_i slowing down and limiting the positive level of P_i. Therefore, the total average pressure inside of the suction cup is negative during the entire vibration cycle.

As can be seen from the process of pressure change, the essence of the model is to regard the boundary of the suction cup as a one-way valve. When in the process of pulling up, the air outside of the suction cup is difficult to enter, however, when in the process of pushing down, the air inside of the suction cup is easy to go out, thus generating negative pressure. In addition, the negative pressure generated by vibration suction is more effective than traditional negative pressure, since vibration suction can directly converts the mechanical energy into the potential energy of the air pressure without other energy loss process.

(2) Mathematical model

Based on our previous research,[29] the volume change of the suction cup in one single cycle can be calculated according to the parameters of the suction cup and vibration source. For the convenience of calculation, the volume of the suction cup is approximately considered as a cone, and the excitation source is simply harmonic vibration in the form of sine wave.

[Insert Figure 2.]

Four different extreme positions in one single cycle are demonstrated in Figure 2, where A is the vibrating amplitude, ω is the vibrating frequency of the suction cup, H_0 is the initial height, H_1 is the initial depression height, and r_0 is the initial radius of the suction cup.

In the nature state, the volume of the suction cup can be expressed as

$$V_0 = \frac{1}{3}\pi r_0^2 H_0 \tag{1}$$

The function of height at random time is

$$h_s(t) = (H_0 - H_1) + A\sin\omega t \tag{2}$$

It is assumed that during the vibration process, the angle θ between the wall surface and the inner surface of the suction cup is a constant, so θ can be calculated as

$$\tan\theta = \frac{H_0}{r_0} = \frac{h_s(t)}{r_s(t)} \tag{3}$$

Therefore, the function of radius at random time is

$$r_s(t) = \frac{r_0}{H_0} h_s(t) = \frac{r_0}{H_0}\left[(H_0 - H_1) + A\sin\omega t\right] \tag{4}$$

At present, the suction cups on the market are basically made of elastic materials and certain elastic deformation δ is generated under the external force. Therefore, the actual functions of the height and radius are calculated as

$$H_s(t) = (H_0 - H_1) + A\sin\omega t - \lambda_1\delta \tag{5}$$

$$R_s(t) = \frac{r_0}{H_0}\left[(H_0 - H_1) + A\sin\omega t\right] - \lambda_2\delta \tag{6}$$

where λ_1 is the longitudinal correction factor of the elastic deformation and λ_2 is transverse one.

During the process of vibrating, the function of the bottom area of the suction cup is

$$S_s(t) = \pi R_s^2(t) \tag{7}$$

Therefore, the functions of volume at random time and the maximum volume change in one cycle are

$$V_s(t) = \frac{1}{3} S_s(t) H_s(t) \tag{8}$$

$$V_\sigma = V_s(t_1) - V_s(t_2) \tag{9}$$

where t_1 is the peak point that the suction cup reaches and t_2 is the through point that the suction cup reaches.

According to (1) and (9), the ratio of volume change in one cycle is

$$V_\varepsilon = \frac{V_\sigma}{V_0} \tag{10}$$

It can be inferred that, the ratio V_ε has a significant effect on suction force. The relationship between V_ε and suction force is positive, which will be verified by the following experiments.

(3) Experimental tests

To verify the above analysis, an experimental platform shown and a vibration source are designed as shown in Figure 3. [Insert Figure 3.]

The experimental platform (Figure 3(a)) mainly includes seven parts: a displacement sensor, an electric motor, a linear bearing, a suction surface which is contacted with the suction cup, a platform frame, a vibration source based on centric slider-crank mechanism and a pressure sensor. The motion of the vibration source is shown in figure 3(b). When the motor rotates, the eccentric wheel and the connecting plate drive the connecting rod to reach up-and-down movement via the connecting base. Meanwhile, the connecting rod drives the suction cup to move up-and-down together by the threaded connector.

The pressure and the displacement sensor of the platform can simultaneously collect the pressure and the displacement signal of the suction cup during the vibration process. The vibration frequency and amplitude are determined by the applied voltage and eccentric wheel respectively. The initial height of a suction cup can be changed by the threaded connection between the suction cup and the rod. In addition, different materials of the substrate which attaches to the suction cup can be changed easily. The substrate of the experiment is made by aluminum alloy with the roughness of *Ra*3.2 approximately. [Insert Figure 4.]

Figure 4(a) shows the internal pressure change of a single suction cup when the diameter and amplitude are invariant. As it can be seen, the initial height can exert a great influence on the suction capacity. It can be inferred that there is a parabolic relation between the ratio of volume change and initial height. The ratio is small when applying a small initial height. However, the ratio will also become small when applying an overlarge initial height because the elastic deformation of the material of the suction cup impedes the vibration process, so that the most vibration has changed into elastic deformation.

Figure 4(b) shows the internal pressure change of a single suction cup when the diameter and initial height are invariant. Obviously, there is also a parabolic relation between suction capacity and the amplitude, which indicates that the suction capacity is small whenever applying too large or too small amplitude. Therefore, it can be inferred that an inappropriate amplitude will also lead to a small ratio.

Figure 4(c) shows the internal pressure change of a single suction cup when the initial height and amplitude are invariant. As it can be seen, a large suction cup will obtain an enhanced suction capacity so that the suction cup can be adhered to the wall.

According to the above three groups of experiments, we can draw the following conclusions:

(1) The suction capacity has a strong relationship with the applied voltage, and the vibration frequency is determined by the voltage. Therefore, there is a certain linear relationship between the suction force of the suction cup and the vibration frequency. Suction capacity gets better when using a larger vibration frequency.

(2) The suction capacity can be analyzed qualitatively by volume change ratio V_ε which is determined by many factors, including the initial height, the radius of suction cup, the vibration frequency and the amplitude.

3. Wall-climbing robot design

(1) Structural design

The body structure of a real gecko is extremely complex. In order to imitate the structure of it, a biological motion model of the real gecko is extracted. The simplification process of a bionic kinematic model is shown in Figure 5. Three revolute joints (joint 1, joint 2 and joint 3 shown in Figure 5(b)) imitating the legged joints of geckos will be introduced in detail in next paragraph.

[Insert Figure 5.]

[Insert Figure 6.]

The wall-climbing robot is mainly comprised of three parts: the central body, legs and the tail, as shown in Figure 6. The function of the central body is to connect with other two parts, and it is also acted as a base for the power supply and control system. In addition, the robot is mainly fabricated with aluminum alloy.

At the end of each leg, there is a vibration suction module as the foot of the robot which can adhere to the wall, namely foot module. In order to move forward, each leg needs to have two-dimensional degrees of freedom (joint 1 and joint 2 shown in Figure 6) parallel to the plane of the wall. In addition, the foot is always in close contact with the wall when it is in the state of adhesion. Therefore, each leg also needs a degree of freedom (joint 3 shown in Figure 6) perpendicular to the plane of the wall to lift the foot so that the foot can move away from the wall during moving process.

The last part is the tail. The role of the tail for this robot is to provide the anti-overturning moment. The tail mainly includes three parts: a regulated motor (joint 4 shown in Figure 6), a tail body and an universal wheel. The function of the motor is to keep the universal wheel and the wall surface in close contact. The tail body, with the length of 358 mm, is connected with the motor and the universal wheel. The universal wheel is used to turn the sliding friction into rolling friction, which can greatly reduce the resistance and the energy consumption.

(2) Design of the suction module

The suction module as the foot of the robot is of vital importance. According to the analysis mentioned above, when the external force is applied to the single suction cup, there still exists positive pressure for a certain period of time although the average pressure inside of the suction cup is negative in a cycle. If the pressure is positive, the suction cup will fall down from the wall. Therefore, it is impossible to achieve a stable adhesion for a single suction cup in a whole cycle. The variation curve of internal pressure, which is in the form of a sinusoid, is instructive for the design of vibration suction module. Equation (11) shows that, when two sinusoids with a phase difference of π but the same amplitude and period superimpose together, the fluctuations of them will cancel each other out.

$$A\sin(2\pi t)+A\sin(2\pi t+\pi)=0 \tag{11}$$

Therefore, a relatively stable negative pressure can be obtained if the designing mechanism causes the two sets of suction cups alternately vibrating with a phase difference of π. In addition, according to the law of three points determining a plane, the number of suction cups is preferably set as three, so two groups need six suction cups. This paper selects two groups with three suction cups for each of the suction module. [Insert Figure 7.]

Figure 7 shows the structure of the vibration suction module, which contains four parts: vibration mechanism, air-releasing mechanism, guidance mechanism and stability keeper.

The core of the vibration mechanism is a centric slider-crank. The red suction cups are connected to the upper base, while the blue suction cup are connected to the lower base (as shown in Figure 7(a)). When the motor drives the eccentric wheel rotates, the upper and the lower base move up-and-down in opposite directions to realize an alternating vibration with a phase difference of π.

The air-releasing mechanism (as shown in Figure 7(b)) is designed to quickly release the module from the wall when it is not working, which is via a steering gear to control the six-way valve, as to control the adhesion status of the suction module. When the module is stably adhered to the wall, the six-way valve is in the closing state. While the module is to be loosened from the wall, the steering gear will pull down the valve core through the eccentric wheel, and the six-way valve is turned on.

A guidance mechanism is designed to make the vibration mechanism move up and down straightly, as shown in Figure 7(b). The mechanism is guided by three linear bearing embedded in the lower base and three guidance pillars fixedly connected with the upper base.

For the foot modules, a stability keeper is designed to prevent the unexpected vibration to the robot body. As shown in Figure 7(a), in order to connect with other components and reduce weight, the holes on the upper face and on the cylinder face are designed. The stability keeper is connected to the module by springs and nuts. The vibration suction module transmits a force to the stability keeper by the spring during the push-down process, while this force will not be transmitted to the stability keeper during pull-up process, which leads to a stability of the robot.

Additionally, the vibration suction module is also mainly consisted of aluminum alloy with the weight of 424g. The diameter is Φ90mm and the height is 55mm.

(3) Test of the suction module

In practical use, excessive load may lead to air leakage through the gap between the suction cups and suction surface, which will cause failures of the foot module. As shown in Figure 8, there are four forms of failures for the vibration suction module, which are vertical pulling force, lateral pulling force, overturning moment and twisting torque respectively. The suction performances of the module are experimentally verified by using a dynamometer (SF500N). [Insert Figure 8.]

The suction performances of the suction module are tested with different substrates: the glass and the wooden board. The vibration amplitude of the suction module used in the experiments is 1 mm and the vibration frequency is 2 Hz.

[Insert Table 1.]

[Insert Table 2.]

Table 1 and Table 2 show that, the suction performance of the module in the vibrating state is better than that in static state, which proves that the vibration can enhance the suction ability of the module.

Table 1 and Table 2 also show that, the suction failure force of the module on the glass is larger than it on the wooden board. This is because the glass surface is smoother than the wooded board surface, which causes a better sealing condition. Similarly, the vibration can increase the capacity of the suction module on sliding failure force, overturning failure flexural moment and twisting failure torque. Meanwhile, they are all larger on the glass surface than on the wooded board surface.

(4) Gait planning

By observing the gait pattern of gecko, we found that 2-3 feet attached to the surface during the process of climbing wall at any time,[30] which are known as diagonal gait and tripod gait. Gecko climbs faster with diagonal gait when preying and running. This gait uses two feet to move, and the other two are adhered to the wall. When in relaxation or position adjustment, the gecko will climb slowly with tripod gait with only one foot to move, and the others are adhered to the wall.

Since the wall-climbing robot usually needs to climb on walls, their suction stability is more important and challenging than mobile robots on the ground. In order to maintain a better capacity of suction, tripod gait will be adopted in this wall-climbing robot. [Insert Figure 9.]

As shown in Figure 9, the robot climbs straightly with tripod gait. The robot moves with four feet at the order of 1-3-2-4. First, the foot 1·moves at the time of t_0, the other three are adhered to the wall. When the feet 2, 3 and 4 move in sequence, the corresponding moments are t_1, t_2 and t_3 respectively. At the time of t_4, four feet are all attached to the wall. The displacement for one cycle of gait is Δs. Please see the dynamic simulation of the robot climbing in Supplementary video S1.

(5) Force analysis

In order to improve the locomotive performance of the wall-climbing robot, a force analysis model needs to be built which will balance the relationship of various forces.

When the robot is climbing on the wall at a constant speed, it bears different kinds of forces. A force analysis is made on a random state posture when the robot climbs vertically on the wall. The study in this case yields a general analysis of the forces equilibrium when the robot is climbing, whose model is built in Figure 10. [Insert Figure 10.]

As shown in Figure 10, the gravity of the robot is G, each vibration suction module has the same suction force F_p, the supporting force is F_{Ni}, the friction force is F_{fi} (i is the number of the foot module and universal wheel). The friction force between the universal wheel and the wall can be regarded as zero because of negligible friction factor of the tail. The perpendicular distance between the gravity center and the wall is t, the distance between the front and rear foot is L, the distance between the universal wheel and the rear foot is a, which is about the same as the tail length, the distance between the left and right foot is s. In addition, the xyz coordinate system is built with the origin at the center of foot 3.

Three feet (foot 1, 3 and 4 shown in Figure 10) are adhered to the wall, while the other (foot 2) is desorbed during the movement. Therefore, the equilibrium equation of forces in the x direction is

$$\sum_{i=1,3,4,5} F_{\mathrm{N}i} - 3F_P = 0 \tag{12}$$

The force balance in the *y* direction when the foot is about to fall off from the wall is

$$\mu \sum_{i=1,3,4} F_{\mathrm{N}i} - G \ = 0 \tag{13}$$

The balance equations of moments in the *y* and *z* direction are respectively

$$F_{N5}\frac{s}{2} + F_{N4}s - F_P s = 0 \tag{14}$$

$$Gt + F_{N1}L - F_{N5}a - F_P L = 0 \tag{15}$$

If the friction force is greater than the gravity of the robot, the robot can be adhered to the wall stably. As we know, the friction force has a close relationship with the supporting force which can be solved by the above four equations, so we can obtain that

$$F_{N1} = (1+\frac{3a}{L})F_P - (\frac{t}{L}+\frac{a}{\mu L})G \tag{16}$$

$$F_{N3} = (\frac{t}{L}+\frac{a}{\mu L}+\frac{1}{2\mu})G - (\frac{1}{2}+\frac{3a}{L})F_P \tag{17}$$

$$F_{N4} = \frac{G}{2\mu} - \frac{F_P}{2} \tag{18}$$

$$F_{N5} = 3F_P - \frac{G}{\mu} \tag{19}$$

When the foot is just off the surface, the supporting force of the wall can be regarded as zero. In this case, based on the results in equations (16) and (17), the suction force can be calculated as

$$\frac{\mu t + a}{(L+3a)\mu}G \le F_P \le \frac{2\mu t + 2a + L}{(L+6a)\mu}G \tag{20}$$

Similarly, according to the results in equations (18) and (19), the suction force can be calculated as

$$\frac{G}{3\mu} \le F_P \le \frac{G}{\mu} \tag{21}$$

Bring the parameters L=390mm, a=358mm, s=287mm, t=17mm and μ=0.8 into the equations (20) and (21), and we can obtain

$$8.4N \le F_P \le 20.2N\ ,\ \ 13.3N \le F_P \le 40N \tag{22}$$

It can be seen that the suction force of the condition that the robot can stably climb on the wall is

$$13.3N \le F_P \le 20.2N \tag{23}$$

From the above Table 1, the suction failure force on the glass is 15.5N, which meets the equation (23). Therefore, the proposed wall-climbing robot is able to climb on the glass window safely.

4. Experiment and discussion

The overall weight of the robot is 3.2 kg including the main body, control system and battery. The total length is 800 mm including the tail, and the width is 324 mm when the robot is climbing in a straight line. The robot consists of nine servomotors, four gear motors and four solenoid valves. Servomotors provide high torques to lift the legs and tail of the robot. Gear motors are used for driving the vibration mechanism. Solenoid valves are used for controlling the separation of the suction module from the wall. In addition, the battery (SCD003) used in the proposed robot can last about half one hour.

The amplitude of the vibration suction module used in this robot is 1mm and frequency is about 2Hz. Each module can produce a certain amount of suction force. When the robot climbs on the wall, three feet are always adhered to the wall at the same time. The suction force generated by the three feet can make the robot climb stably. Figure 11(a) shows the robot is climbing on the surface of a glass window and the maximum climbing speed can reach 13.75 mm/s with a load of 500g. As shown in Figure 11(b), it can accomplish a point-turn motion, the single minimum turning angle is about 20°. Owing to the bionics of gecko's gaits, the robot has the features of fast climbing and relative good payload capacity with a simple structure. In addition, the robot has a large suction force and strong environmental adaptability since the vibration suction module is adopted as the foot of the robot.

[Insert Figure 11.]

The experimental results demonstrate that the feasibility and robustness of the robot are appreciable. However, some improvements still need to be carried out in the future. Firstly, compared with the test of one single foot, the vibration suction modules are suffered from a more complicated stress state during the movement of the robot and a slight unintended left-right vibration happens, which will affect the overall robustness of the robot. Some possible solutions to this problem include optimizing the guiding mechanism of the foot module, reducing the assembly clearance or adding some lubricating fluid. In addition, the structure of the robot body is mainly fabricated with aluminum alloy, which limits the load capacity of the robot. In the future, weight reduction should be carried out, and some parts can be replaced with lighter materials, such as PVC, carbon fiber board, etc. Finally, the size of the robot structure is too large especially for the leg, so the torque of the robot foot relative to the central body is too large, resulting in insufficient suction force to support its climbing on the vertical wall. The length of each leg can be redesigned to get a better length value to optimize the robot.

5. Conclusion

This presented a robot which combines the vibration suction mechanism with the motion gait of geckos. Compared with the traditional wall-climbing robots based on negative pressure mechanism, the proposed robot using vibration suction mechanism has advantages of no need of gas source, large suction force and strong environmental adaptability. In addition, experiments have shown that the robot can climb the vertical surface of the glass at the maximum speed of 13.75 mm/s, and it also can make a spot turning with the single maximum turning angle of 20°.

Optimizing the structure of the vibration suction module and the overall structure of the robot should be included in the future work. Obstacle avoidance, autonomous navigation, and some peripheral devices for specific scenarios will be addressed in the next prototype.

Conflict of interest

None declared.

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