Structure Design and Mobility Analysis of a Climbing Robot

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Abstract. RiSE and LEMUR IIB have good climbing ability. Inspired by these two robots, a new climbing robot with simplified motion mode and strong load capacity is proposed. In this paper, the structure of the robot is introduced detailedly. Through the dynamic analysis of its leg and body, the torque of the traction and swing motor under various driving modes are obtained. Static analysis of the robot's claw is also carried out during the climbing process. Meanwhile, the equivalent tangential force and normal force required for the claw attached to the wall are described. The results indicate that the robot has high mobility and can successfully realize the climbing movement.

1. Introduction

Most of climbing robots usually use magnets [1-3], suction [4-5] or adhesives [6-7] to obtain the ability to walk and stay on vertical surfaces. However, these approaches are limited in certain cases. Magnetic adsorption is only applicable to the surface of ferromagnetic materials, suction method is prone to gas leakage on cracked or uneven wall surfaces, while adhesion is easy to be contaminated by dust and fails. A more general and useful robot would be capable of climbing a wide variety of rough and dusty wall surfaces, where specialized attachment mechanisms such as magnets, suction and adhesives are unsuitable.

Claws are prevalent in insects, and almost all insects are involved in claws when climbing on rough walls. By observing the legs and claws of animals such as insects and geckos and drawing on their physiological morphology and structural characteristics, the researchers have carried out much work on the microspine climbing robots and obtained fruitful achievement. Since 2005, Boston Dynamics in the United States has developed three generations of RiSE series climbing robots. RiSE V1 has six legs, using tripod gait to realize stable crawling on rough tree trunks [8-9]. RiSE V2 optimized the structure of RiSE V1, enhancing the flexibility and adaptability of the climbing robot [10]. RiSE V3 redesigned the leg transmission mechanism and claw structure, greatly improving the robot's climbing speed [11]. The Jet Propulsion Laboratory (JPL) has developed the DROP prototype [12-13], which is capable of climbing 90° walls made of cinder block or other rough materials. Then, JPL also develops a rock-climbing robot named LEMUR IIB [14-15], which has four grippers, each with over 250 microspines distributed in 16 carriages. LEMUR IIB grips the rock using hierarchical arrays of microspines and can free climb on vertical rock faces. In addition, Liu Yanwei [16-17], Clark [18-20], Daltorio [21], Birkmeyer [22] and others have also carried out relevant research on climbing robots, and proposed various claw structures and specialized climbing behaviors, which further promoted the development of climbing robot technology.

RiSE and LEMUR IIB, as the typical representatives of the current climbing robots, have excellent climbing performance. However, only several flexible microspines of RiSE V1 and V2 difficultly bear...
a larger load, and RiSE V3 relies on single hardened needle and has poor environmental adaptability. LEMUR IIB overcomes the shortcomings of RiSE, but its leg structure is relatively complex and gait control is too difficult for daily applications. Some optimization can be conducted for these robots to meet the special requirements. Inspired by RiSE and LEMUR IIB, a new climbing robot with simplified motion mode and strong load capacity is proposed. In this paper, the structure of this climbing robot is presented firstly. Then the mechanical analysis of three important parts of the structure, including the leg, body and claw, is carried out respectively to verify its mobility and load capability.

2. Structure Design

Refer to the physiological characteristics of the gecko, the climbing robot is designed into a four-limbed form, as shown in Figure 1. The legs and claws are symmetrically distributed on the left and right sides of the base plate, using modular design concept. The electronic control system is located in the middle of the base plate, driving the servo motors of the legs and the claws to move along the desired trajectory.

![Figure 1. The overall structure of the climbing robot](image)

The main function of the leg structure is to realize the alternating movement of claw, and then to complete the walking and climbing action of the robot. Considering the simplicity of structure and control, it is determined that each leg has two active degrees of freedom (DOFs), which are called the traction DOF and the swing DOF, respectively. The swing DOF is driven directly by the swing motor and gear set, and its trajectory is approximately circular. It is used to fulfill the function to get the claw close to and away from the wall. As shown in Fig. 2 (a), the maximum range of the swing angle $\alpha$ is $-15^\circ$-$15^\circ$. Different from the direct drive of the swing DOF, the traction DOF makes use of the excellent transmission characteristics of the four-linkage mechanism. By adjusting the size parameters of the four linkages, the claw’s motion trajectories of various shapes can be obtained, so as to facilitate the gait planning of the robot. The final motion trajectory of the claw center chose by the robot is shown in Figure 2, which is approximately contained two parts: line segment and elliptic segment. When the crank of the four-linkage mechanism moves from point A to point B ($\angle AOB=120^\circ$), the center of the claw is on the line segment ab. When the crank moves to point C ($\angle AOC=225^\circ$), the center of the claw is located at the farthest point C of the trajectory.
Furthermore, the leg structure also includes two passive flexibility DOFs, as shown in Figure 3. When the lateral translation of the claw occurs, the buffers located on both sides of the four-link mechanism will produce elastic expansion or compression, automatically adjusting the force on the claw. And, the rotating flexible structure in the longitudinal direction is designed to make as many the mirospines attached to the wall as possible, thus improving the grasping performance of the claw, avoiding rigid contact with the rough wall, and enhancing the ability of the claw to adapt to complex surface environment.

Learning from LEMUR IIB, the claw structure is designed as shown in Figure 2 and 3, which adopts the circumferential grasping mode. The claw structure contains 160 flexible mirospines distributed uniformly in 16 carriages. Each two opposing carriages form a pair-gripper. And each two adjacent carriages exist independently, and have their own motion space to avoid mutual interference. The claw is divided into two parts of the attachment and detachment system. When the claw is in contact with the wall, the gripper motor drives the carriages to slip on the wall surface. Once the
bulges or pits are encountered, the lock will be created to achieve the attachment. When the claw needs to leave, the detachment motor acts by pulling the inner wire rope and lifting the carriages to separate them from the wall. Flexible buffer units such as springs are installed in each part of the claw structure to reduce the rigid contact stress with the wall and to increase the stability of the grasping. The claw is connected with the leg structure through the connecting ring. During the climbing process, the claw can rotate axially around the connecting ring in a limited range to improve the flexibility of movement.

Figure 4. The physical prototype of the leg and body

This climbing robot simplifies its structure and control in several ways. (1) The leg structure has two DOFs, less than that of LEMUR IIB with three. (2) Compared with RiSE, the two DOFs of the leg structure are closer to direct driven by the motor, through minimizing the intermediate transmission chain. (3) The two DOFs are independent of each other and have no coupling relationship, which can reduce the difficulty of control. However, the robot still has high motility, flexibility and adaptability with the assistance of passive flexible DOFs, even though there is some simplification in the structure. And its climbing performance and load capability is relatively better than RiSE since the claw of the robot uses the circumferential grasping mode of LEMUR IIB and there are more microspines attached on the wall at the same time. So far, the design, processing and assembly of the leg and body structure of the climbing robot have been completed, as shown in Figure 4.

3. Dynamics analysis of the leg

On the basis of the three-dimensional structure of the robot, the simulation model is established. Through adding the rotary driving pairs to the output position of the traction and swing motor in Adams, the kinematics and dynamics of the leg structure can be analyzed. As shown in Figure 2, during the movement of the four-linkage mechanism, the distance d1 from the center of the claw to the rotation center of the swing DOF will change continuously, which can affect the swing torque. Therefore, three typical positions of A, B and C are selected on the motion trajectory, to obtain the driving torque of the swing motor at each point, and then the variation law of the swing torque can be discussed. The traction and swing driving functions are set up as shown in formula (1) and (2), respectively. The values of the parameters in the formulas are shown in Table 1.

The traction function: \[\text{step (time, 3T, 0, 5T, } \theta_a) + \text{step (time, 8T, 0, 10T, } \theta_b) + \text{step (time, 13T, 0, 15T, } \theta_c)\] (1)

The swing function: \[\text{step (time, 0, 0, T, } -a) + \text{step (time, T, 0, 2T, } 2a) + \text{step (time, 2T, 0, 3T, } -a) + \text{step (time, 5T, 0, 6T, } -a) + \text{step (time, 6T, 0, 7T, } 2a) + \text{step (time, 7T, 0, 8T, } -a) + \text{step (time, 10T, 0, 11T, } -a) + \text{step (time, 11T, 0, 12T, } 2a) + \text{step (time, 12T, 0, 13T, } -a)\] (2)

The analysis results are shown in Figure 5. According to the motion trajectory, during the movement, it swings up and down at points A, B and C in turn, and finally returns to the starting point A. From the torque curve, it can be seen that the variation range of the swing torque at point A and point B is 1.15~1.48Nm, and that at point C is 1.39~1.81Nm. Obviously, the swing torque is the
largest when the claw is at the farthest point C and the force arm d1 is the longest. It also can be seen that, when the swing angle \( a \) is \(-15^\circ\), the swing torque of A, B and C point is 1.15 Nm, 1.15 Nm and 1.39 Nm, and when the swing angle \( a \) is \(15^\circ\), the torque is 1.48 Nm, 1.48 Nm and 1.81 Nm. This shows that the variation of swing angle \( a \) has a certain influence on the swing torque, and its fluctuation is about 0.33~0.42Nm.

Figure 5. The analysis results of the swing DOF ( (a) motion trajectory  (b) torque curve )

Table 1. The parameter values of the traction and swing driving functions

| Parameter | T | \( \theta_a \) | \( \theta_b \) | \( \theta_c \) | \( \theta_0 \) |
|-----------|---|-------------|-------------|-------------|-------------|
| Value     | 1s | \(15^\circ\) | \(120^\circ\) | \(105^\circ\) | \(135^\circ\) | \(360^\circ\) |

Because of the interaction between the traction and swing DOF, the dynamics analysis of the traction DOF is carried out when the swing angle \( a \) is \(-15^\circ\), \(0^\circ\) and \(15^\circ\). The traction and swing driving functions are set up as shown in formula (3) and (4), respectively. And the analysis results are shown in Figure 6. According to the motion trajectory, the traction DOF rotates one cycle each when \( a \) = \(-15^\circ\), \(0^\circ\) and \(15^\circ\). From the torque curve, it can be seen that the driving torque of the traction DOF varies from 0 to 0.45 Nm, and the swing angle \( a \) has little influence on the traction torque. It should be noted that this result is only for the leg structure. In the actual climbing process, the maximum driving torque of traction DOF is greater than 0.45 Nm, because it needs to push the whole body upward.

The traction function: step (time, T, 0, 5T, \( \theta_0 \)) + step (time, 6T, 0, 10T, \( \theta_0 \)) + step (time, 11T, 0, 15T, \( \theta_0 \))

\[(3)\]

The swing function: step (time, 0, 0, T, \(-a\)) + step (time, 5T, 0, 6T, \(a\)) + step (time, 10T, 0, 11T, \(a\))

\[(4)\]

Figure 6. The analysis results of the traction DOF ( (a) motion trajectory  (b) torque curve )

4. Dynamic analysis of the body
LEMUR IIB moves one leg forward at a time and then the corresponding claw reattaches to the wall. When all four legs have moved, the body follows one step forward. Due to structural differences, the body movement mode of this robot is not completely the same as that of LEMUR IIB. Without considering the swing DOF, the schematic diagram of the robot described only in the climbing plane is shown in Figure 7. As can be seen, each claw is rotatably connected with the linkage, and four frames are fixed on the same base plate. Obviously, when the four or three claws grasp the wall at the same
time, the body is in an over-constraint state, and the traction motors cannot drive it movement. If there are two claws attached to the wall surface, the DOF of the body is obtain as

\[ F = 3n - 2PL - PH = 3 \times 7 - 2 \times 10 - 0 = 1 \]  

(5)

It means that only one motor is needed to drive the body forward in this condition.

Figure 7. The schematic diagram of the robot in the climbing plane

In the diagonal gait, it is called “pull” mode if the body is driven only by the front traction motor, and “push” mode if the body is driven only by the rear motor. Between the two modes, the maximum driving torque required is different. Through the simulation analysis, the left front (LF) and right rear (RR) traction motor is used respectively, to drive corresponding crank rotate 120° from the starting point A to point B, so as to move the body forward one step. The driving functions of LF and RR legs are set up as shown in formula (6), and the analysis results are shown in Figure 8 and 9.

The traction function: step (time, T, 0, 4T, \( \theta_a \))

(6)

Figure 8. The torque curve in the pull mode  
Figure 9. The torque curve in the push mode

It can be seen that, in the pull mode, the maximum torque of the LF traction motor is about 2.68 Nm, the holding torque at point A is about 1.5 Nm, and the holding torque at point B is about 0.65 Nm. In the push mode, the maximum torque of the RR traction motor is about 2.41 Nm, the holding torque at point A is about 1.0 Nm, and the holding torque at point B is about 1.25 Nm. In addition, the variation trend of the two torques is similar. They both rise first and then fall, but the position where the maximum torque occurs is different.

However, it is generally not appropriate to use single motor drive in the actual operation of the robot. Although there is only one DOF, due to the existence of passive flexible DOFs and the synchronous control of the motors, the use of two motors to pull and push the body upward at the same time is feasible, which would be more stable and reliable. The spring elements are added to the previous simulation model, and the body is driven meanwhile by the LF and RR motors. The torque curves are measured as shown in Figure 10. It can be seen that the maximum output torque of the two motors has been effectively reduced, in which the torque of the LF motor is 1.43 Nm, while that of the RR motor is 1.22 Nm.
Figure 10. The torque curves of the dual-motor drive mode
(a) left front motor  (b) right rear motor  unit: sec-mNm

Furthermore, four traction motors are used to drive the body upward at the same time, and the torque curves of each motor are obtained as shown in Figure 11. It can be seen that, the maximum driving torque of each motor is further reduced, in which the output torque of the two front motors is about 0.85 Nm, while that of the two rear motors is less than 0.04 Nm. Obviously, the output torque of the rear motor is much smaller than that of the front motor. This means that the front motors pull hard while the rear motors push lazily. Because the motion trajectory of the four-linkage mechanism is not completely symmetrical, the motion of the front legs is slightly ahead of the rear legs, which causes the two front motors to work harder.

Figure 11. The torque curves of the quadra-motor drive mode
((a) left front  (b) right front  (c) left rear  (d) right rear  unit: sec-mNm)

It should be noted that in the previous two sets of simulation analysis, the load of the traction motor is the weight of the body and two claws, because there are two claws fixed to the wall while the body and the other two claws are relatively free and needs to be driven upward. In the analysis of four-motor drive mode, the load is only the weight of the body because all four claws are fixed to the wall. This is one of the reasons that the output torque is small in four-motor drive mode. Both the motors used by the leg structure of the robot are the 20W DC servo motor (Maxon DCX22S), with a 439:1 gear ratio, and its rated output torque is 5.93Nm. There is no doubt that this servo motor can meet the requirements.

According to the above analysis, it can be seen that the robot has good mobility and adaptability. There are three drive modes of the mono-motor, dual-motor and quadra-motor. No matter which drive mode is adopted, the body of the robot can be pulled upward effectively. Further analysis shows that the mass of an external load, placed in the middle of the body, can be up to 5.1kg, even in the mono-motor drive mode. This indicates that the robot has the potential to bear heavy load.

5. Static analysis of the claw
As shown in Figure 12, under the diagonal gait, the climbing process of the robot can be divided into four stages: (1) The robot is in the initial state. Four claws are attached to the wall. The cranks of the four-linkage mechanism are located at the starting point A. (2) Each of the four traction motors drive its corresponding crank to rotate 120° to point B, pulling the body of the robot to move upward
one step. The distance of the body movement $s$ is about 100 mm. (3) The LF and RR claws detach from the wall while the right front (RF) and left rear (LR) claws still grasp it. The crank of the LF and RR cranks rotates back to the point A, driving the claws to move one step upward and then reattach to the wall. (4) Next, the RF and LR claws detach from the wall, the cranks of the RF and LR legs rotates back to the point A, driving the claws to move forward and then reattach to the wall. At this point, the robot returns to its original position and completes one step. Repeatedly, the climbing motion of the robot is realized.

Figure 12. The climbing process of the robot

During the climbing process, the force of the claw attached to the wall will change with the motion variation of the robot. To simplify the analysis, the force on each claw is equivalently decomposed into two parts, the tangential force $T$ along the $-z$ direction and the normal force $N$ along the $-y$ direction, as shown in Figure 13. The tangential force $T$ is to balance the self-weight and load, while the normal force $N$ is to prevent itself from flipping.

Figure 13. The equivalent force on the claw

Stage (3) and (4) of the climbing process have similar static force condition, with only two claws attached to the wall, which requires relatively higher tangential force and normal force. Therefore, static analysis of the claws is carried out on the entire motion process of stage (4). The simulation
model is established. High stiffness springs along -y and -z directions are respectively arranged between the LF claw and the ground, so as the RR claw and the ground. The tangential force and normal force of the two claws are obtained by measuring the spring force. This method of static analysis utilizes the principle of virtual displacement. The driving functions of the RF and LF legs are set up as shown in formula (7) and (8), and the analysis results are shown in Figure 14.

The swing function: step (time, T, 0, 4T, a) + step (time, 7T, 0, 10T, -a)  
The traction function: step (time, 4T, 0, 7T, θa)  

\[
\begin{align*}
\text{(7)} \\
\text{(8)}
\end{align*}
\]

It can be seen that in order to maintain the static balance of the stage (4), the tangential force \( T \) and normal force \( N \) required for the claws attached to the wall surface should be not less than 27.8 N and 8.6 N. The swing angle \( a \) has a certain influence on the normal force. When \( a \) is 0°, the normal force is about 6.9 N. As the swing angle increases, the center of gravity of the claw also rises. To avoid flipping, a greater normal force is needed. In the actual operation of the robot, if there is no high obstacle, small swing angle \( a \) should be adopted, such as 4° ~ 8°.

During the design of claw structure, the load capacity of the single microsipne and the whole claw should be fully considered to ensure the reliable attachment on the wall. The gripper of LEMUR IIB can support more than 130 N normal force and 140 N tangential force to the surface of the rock [15]. According to the gripper of LEMUR IIB, it is completely possible to achieve effective attachment since the tangential and normal force required for this robot is relatively small.

6. Conclusion and future work
This paper introduces the overall structure of the climbing robot. By analyzing the dynamics of leg and body, the torque curves of the traction and swing motor under various driving modes are obtained. The results show that the robot has good mobility, and can successfully complete the wall climbing movement. Then the equivalent tangential force and normal force required for the claw attached to the wall are described under the condition of dual-claw attachment, which provides a theoretical basis for the detail design of the claw structure. In future, the climbing experiment will be carried out. The actual output torque of the motors in the real working environment will be measured and compared with the results of simulation analysis. The tangential force and normal force of the claw will also be measured to verify its load capability.

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