Design of a Foot-End Three-Axis Force Sensing Module for Gecko-Like Robot

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Abstract: The problems of attachment failure and detachment impact within gecko-like robots' locomotion control are considered in this paper. A real-time foot-end force intelligent sensing module with integrated sensing and structure is developed to help the robot get the foot-end force information in time and realize stable locomotion in an uncertain environment. Firstly, a structure/sensing integrated elastomer based on a Maltese cross /cantilever beam structure is completed by designing and finite element analysis. Secondly, a real-time data acquisition and transmission system is designed to obtain the foot-end reaction force which is miniaturized and distributed. Thirdly, based on this system, a force sensor calibration platform is built to complete the calibration, decoupling, and performance testing of the sensing module. Finally, the experiment of single-leg attachment performance is carried out. The results indicate that the three-axis sensing module can detect robot's weight, measure the reaction force with high precision and provide real-time force from robot's foot end.

Key words: foot-end force sensing module; highly precise and real-time system; force control; gecko-like robot

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0 Introduction

The wall-climbing robot is a new type of robot. It combines the key technologies of mobile robots and attachment technology and has been widely used in high-risk tasks, like building inspection[1], ship inspection, and anti-terrorism warning. Among many wall-climbing robots, the legged wall-climbing robot has become a research hotspot because of its all-round and flexibility of movement and adaptability to the wall environment.

According to the contact situation between the legged attachment climbing robot and the climbing surface, some research teams divided the whole movement cycle of the legged attachment wall-climbing robot into the attach phase, the standing phase, the detach phase, and the swing phase[2]. The difficulty of investigating the motion control of the attachment climbing robot is to achieve stable attachment[3] between the robot and the climbing surface and compliant detachment. The stable attachment ensures that the robot has sufficient tangential attachment traction to overcome the gravity of the fuselage and load and to climb forwards, while the compliant detachment can effectively reduce the impact between the robot and the contact surface during the detachment process. For the method of attachment and detachment of robots, scholars conducted systematic testing and research. Geckobot achieves the robot's compliant detachment through the active detachment device, but the open-loop position control cannot guarantee the stable attachment of the robot to the climbing surface[4]. as a result, Geckobot's climbing angle on the wall cannot

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reach 90°. Stickybot has a tangential force sensor on the elbow[5]. Through the mechanical information of the sensor, Stickybot realizes the tangential force regulation during the robot detachment process. RiSE uses the foot-end two-dimensional force sensor to efficiently climb up through the closed-loop force control to achieve stable attachment and compliant detachment when climbing[6]. Compared to Geckobot's zero-sensing open-loop position control mode, Stickybot and RiSE improve the motion stability of the robot by using a force-aware closed-loop force control mode. However, Stickybot cannot sense the normal force and does not guarantee stable attachment during climbing, while RiSE's force sensing module can help it achieve stable upward climbing, but for the foot aiming to achieve omnidirectional performance, the two-dimensional force sensing module is not suitable. Therefore, the development of the three-axis force sensing module for the attachment climbing robot is the basis for the stable attachment and compliant detachment of the attachment climbing robot.

The three-axis force sensing module of the foot robot should be designed according to the performance requirements and structural characteristics of the robot. Xu et al.[7] combined FSS force sensor and 3D printing technology, and designed an assembled three-axis force sensor for robot reaction force detection. Ding et al.[8] used four FSS force sensor arrays to design a foot bionic robot foot-end mechanism with three-axis force-sensing capability. The mechanism has load-bearing and external force-sensing functions. Xu et al.[7] designed the sensor range of 0—2.5 N, the load capacity is poor; Ding et al.[8] designed the three-axis force sensing mechanism range of 0—15 N, but the accuracy is only about 10%; RISE's designed strain-based two-dimensional force sensing module has a range of 0 to 20 N and measurement accuracy of 0.25 N, but the size is large.

In order to realize the three-axis force sensing of the contact surface of the adhesive climbing robot, this paper designs a three-axis force sensing module of the foot-end based on the principle of strain sensing. The three-axis force sensing module is capable of sensing the reaction force between the foot-end and the wall environment. The structural design of the elastomer and signal processing module integrated into the leg can significantly reduce the size of the leg mechanism. Besides, to design a force sensing system suitable for an adhesive climbing robot needs the following prerequisites: The accuracy and range of the force sensor should meet the needs of most foot-climbing robots, which must have good dynamic characteristics and overload capability. It is possible to reliably measure the interaction between the foot-end and the wall during the climbing process.

Our approach is conducted as follows. First, according to the operational requirements of the adhesive wall-climbing robot, the structure/sensing integrated design of the three-axis force sensing module is completed. Second, the finite element analysis of the sensor elastic body is carried out to verify the feasibility of the measurement principle. Third, a real-time data acquisition/transmission system is designed according to the fast reaction force and steps in the process of attachment and detachment of the wall-climbing robot, and a calibration platform is built on this basis to complete the calibration, decoupling, and test of the three-axis force sensing module of the foot-end. Finally, combined with the mechanical information of the foot-end, the admittance control algorithm is successfully used to verify the single-leg attachment test of the climbing wall robot.

1 Design of Three-Axis Force Sensing Module

1.1 Structure/sensing integrated design

The force sensing module is mounted at the foot-end of the robot, which is used to sense the magnitude and direction of the reaction force between the foot-end of the robot and the wall environment, and return the force data to the control system of the robot. Combined the ideas of the integrated design of the sensor module and the resistance strain sensor, the integrated design of the structure/sensing of the force sensing module is shown in Fig.1. The three-axis force sensing module is composed of the following parts: (1) The upper connector, (2) covers, (3) supports, (4) the signal board, (5) the elastomer, (6) lower connectors, (7) fix staff, (8) the ball bearing, (9) the footpad, (10) adhesion materials.

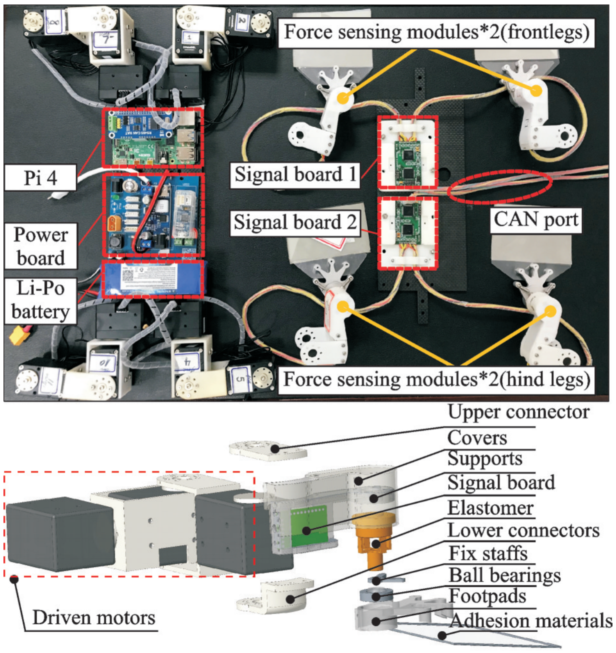


Fig.1 Constitutions of force sensing module

The force sensing module functions as both foot three-axis force measurement and load support. Therefore, considering the operational requirements of the wall-climbing robot, the structure of the three-axis foot force sensor and its elastomer should comply with the following rules. (1) High overload capacity: During the climbing and detachment process, the foot of the robot will produce a large impact force with the contact surface, so the elastic element with a large overload capacity can avoid the occurrence of sensor damage and failure. (2) Simplified elastomer structure: The elastomer structure of a multi-axis force sensor is complex and the structural design is much more difficult than that of the uniaxial sensor. Therefore, the structure design of the elastomer is as simple as possible to avoid the unnecessary trouble caused by the complex structure design for the elastic processing of sensors.

Therefore, after comprehensive consideration of various factors, the design index of three-axis foot-end force sensor is set, as listed in Table 1.

Table 1 Design parameters of force sensing module

Range/ N	Resolution/ (%FS)	Length/ m	Width/ m	Height/ m	Overload capacity/ (%FS)
0—10	⩽1	⩽0.03	⩽0.03	⩽0.035	⩾300

1.2 Principle analysis and finite element simulation of foot-end three-axis force sensor

As shown in Fig.2, the three-axis force sensor is composed of an elastomer, an upper connector, and a lower connector. An elastomer is the element that converts external load (multi-dimensional force) into a strain variable[2], which is the core of the whole sensor. The three-axis force sensor adopts the cantilever beam structure in the tangential direction, which has the advantages of moderate stiffness, high sensitivity, and good stability.

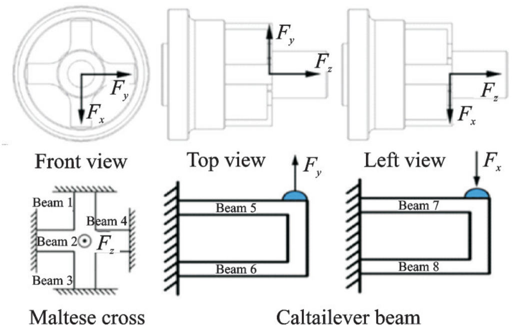
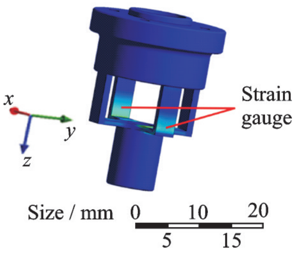
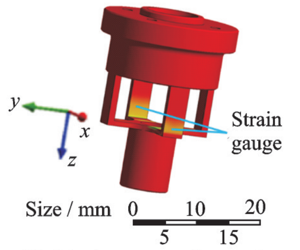


Fig.2 Structure of elastomer

In the finite element analysis, when the upper connector is fixed and the tangential force load F is applied at the end of the lower connector, the maximum strain occurs at the upper and the lower surfaces of the sensitive parts of the strain beam, namely the placement position where the strain gauge is designed, as shown in Figs.3, 4. The three-axis force sensor adopts the Maltese cross structure[9] as the design scheme in the normal direction. This struc-

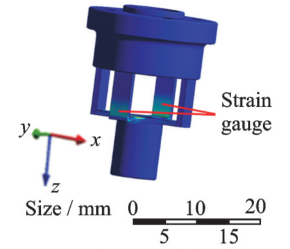


(a) Maximum positive strain

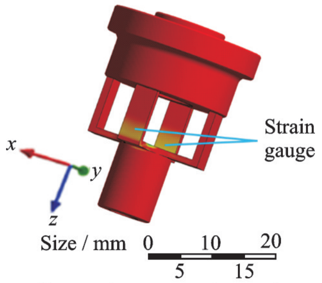


(b) Maximum negative strain

Fig.3 Analysis of the x axis's tangential stress of the strain beam



(a) Maximum positive strain

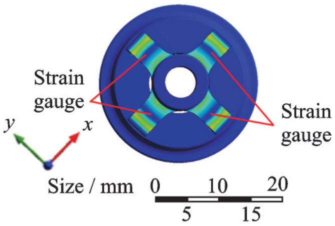


(b) Maximum negative strain

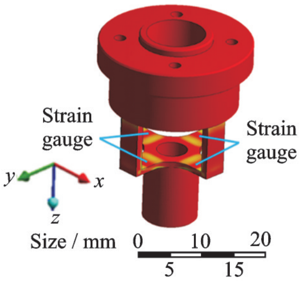
Fig.4 Analysis of the y axis's tangential stress of the strain beam

ture has a large overload capacity in the normal direction, high normal stiffness, and moderate sensitivity. In finite element analysis, the maximum strain occurs in the middle of the four beams (Fig.5). The strain gauge on the patch can effectively convert the strain of the sensor elastomer into a change in the resistance value.

There are four groups of Wheatstone full-bridges on the sensor elastomer, among which, in the upper and lower surface strain sensitive area of Maltese cross structure (Fig.2), eight resistance strain gauges jointly constitute two groups of Wheatstone full-bridge circuits, which are used to detect the force and direction of the sensor elastomer in the normal z direction. The elastic body of the sensor is a cantilever beam structure in x and y tangential directions. Here, only x direction is analyzed. When the sensor elastomer is the tangential force along the x direction, the upper surfaces of beam 1, beam 2 are in the positive stress (strain), and the lower surfaces of beam 1, beam 2 are in the negative stress (pressure). Therefore, the resistive strain gauge in Wheatstone full-bridge circuit is composed of these four strain sensitive areas, which can realize the detection sensor elastomer force in the x-direction. In the same way, the y-direction is also tested by a set of Wheatstone Bridges, as shown in Fig.6.



(a) Maximum positive strain



(b) Maximum negative strain

Fig.5 Analysis of the z axis's tangential stress of the strain beam

The output voltage of each bridge is set as ΔU_1, ΔU_2, ΔU_3, ΔU_4, then the measurement method can be expressed as

$$\begin{cases}\Delta U_x = \Delta U_1 + \Delta U_2 \\ \Delta U_y = \Delta U_3 \\ \Delta U_z = \Delta U_4\end{cases} \tag{1}$$

where ΔU_x, ΔU_y, ΔU_z represent the variation of the corresponding electrical signal generated by the force exerted on the robot in the coordinate system at the foot.

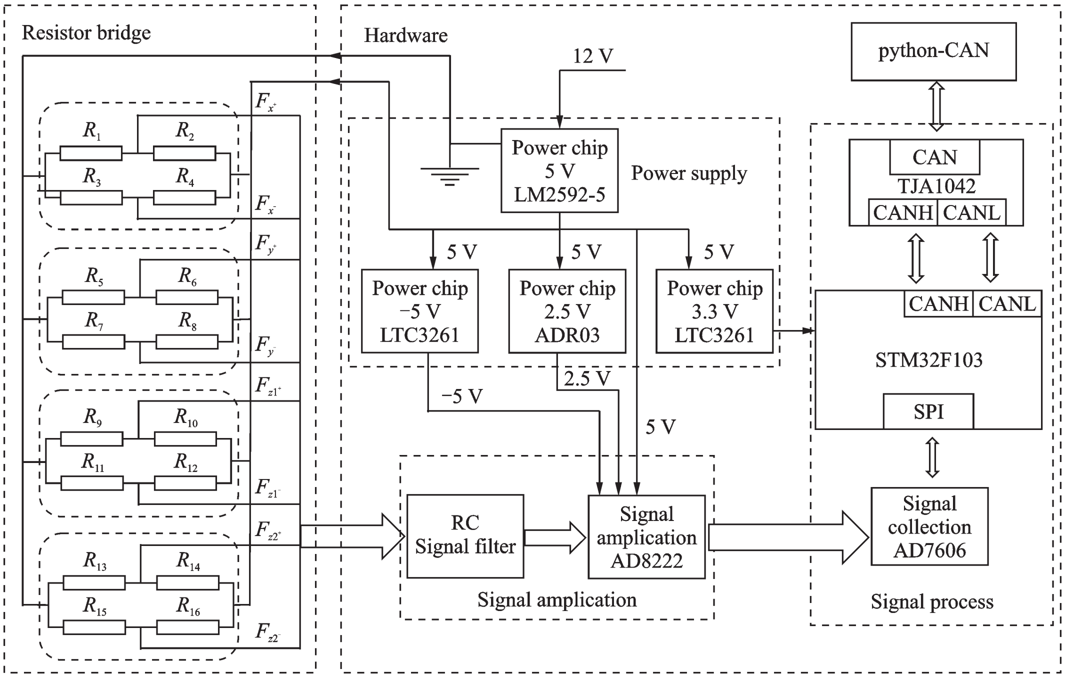
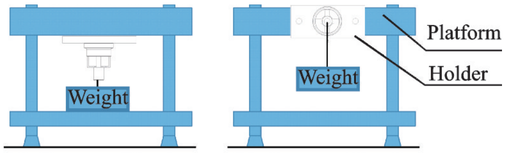


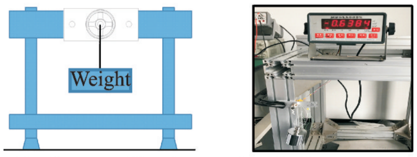
Fig.6 Design of resistor and hardware

2 Sensor Static Calibration and Decoupling

The calibration of the resistance strain gauge force sensor is the basis of sensor measurement. The corresponding relationship between force and voltage signal is established through calibration. During the calibration, the known weight is loaded to measure the output voltage of the bridge, and the mathematical model between the force and the voltage is established. In this way, when the sensor is used, the force direction and magnitude of the sensor can be obtained by measuring the output voltage. Due to the special structure of the sensor, coupling parameters of the sensor need to be obtained through calibration. The calibration of the three-axis force sensor on the foot-end of the robot is carried out by hanging weights in three directions (Fig.7).



(a) Sensor calibration in *z* direction (b) Sensor calibration in *x* direction



(c) Sensor calibration in *y* direction (d) Calibration device

Fig.7 Schematic diagram of sensor calibration

Due to the structure and patch mode of the sensor elastomer, as well as the difference between the elastomer processing error and the strain gauge effect, there is a coupling between the three axises of the sensor. Therefore, before using the three-axis force sensor, it is necessary to calculate the decoupling matrix of the sensor through static calibration of the sensor, establish the algebraic relationship between force vector F and bridge output voltage vector U, and solve the problem of three-axis coupling.

The static calibration adopts the signal conditioning device of the NST400 system, and the output of the four gauge bridges are connected to the NST400 system. Fixed weights are loaded on the x, y, and z directions of the sensor, and three axes of the sensor are measured each time. Through the acquisition software of the upper computer, the calibration data can be obtained, and then the slope and linearity of the output curve of the sensor can be calculated through the fitting data. The ideal situation of the three-axis force sensor is that when force is exerted in x, y, and z directions, the output of the gauge bridges in each direction will not affect each other. However, the directions of the force sensor are not independent from each other, and there is a dimensional coupling. The relationship between the variation of bridge voltage signal and the force exerted on the sensor should be

$$\begin{bmatrix}U_{1x}\\U_{1y}\\U_{1z}\end{bmatrix}=\begin{bmatrix}A_{xx}&A_{xy}&A_{xz}\\A_{yx}&A_{yy}&A_{yz}\\A_{zx}&A_{zy}&A_{zz}\end{bmatrix}\begin{bmatrix}F_{1x}\\F_{1y}\\F_{1z}\end{bmatrix}=TA*F \tag{2}$$

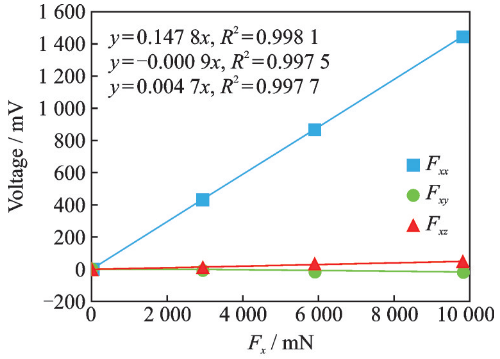
By substituting the data obtained from the calibration into Eq.(2), Eq.(3) can be obtained

$$\begin{bmatrix}U_{1x}\\U_{1y}\\U_{1z}\end{bmatrix}=\begin{bmatrix}0.147\,7&-0.000\,9&0.004\,7\\0.010\,7&0.140\,3&-0.007\,5\\0.016\,2&-0.006\,1&-0.064\,3\end{bmatrix}\begin{bmatrix}F_{1x}\\F_{1y}\\F_{1z}\end{bmatrix} \tag{3}$$

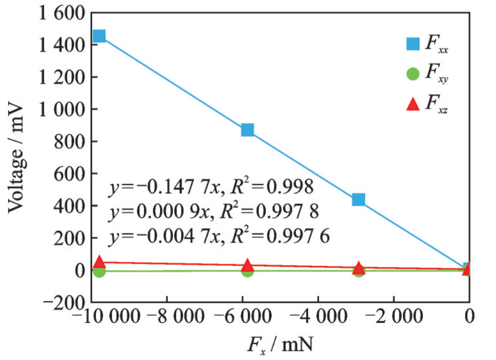
By calculating, Eq.(4) is obtained.

$$\begin{bmatrix}F_{1x}\\F_{1y}\\F_{1z}\end{bmatrix}=\begin{bmatrix}6.819\,6&0.065\,1&0.490\,9\\-0.608\,9&7.085\,8&-0.870\,9\\-1.660\,0&-0.688\,6&-15.593\,1\end{bmatrix}\begin{bmatrix}U_{1x}\\U_{1y}\\U_{1z}\end{bmatrix} \tag{4}$$

Then, the three-axis force of the foot sensed by the sensor can be obtained through the change of resistance bridge voltage and the decoupling matrix. The results are shown in Figs.8—10 and Table 2.

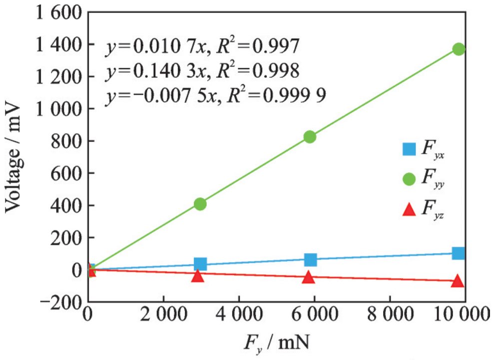


(a) Load/unload force through x^+

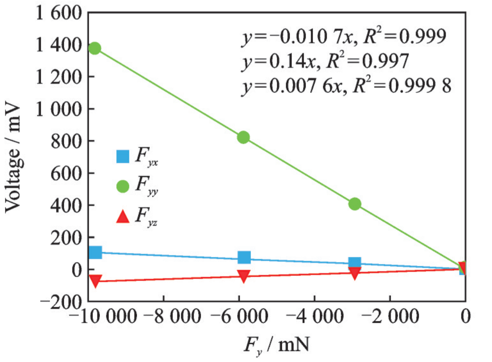


(b) Load/unload force through x^-

Fig.8 Sensor characteristic of x axis

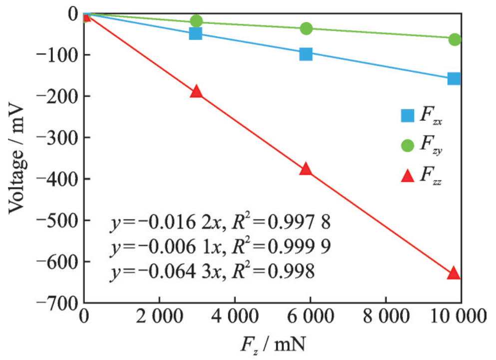


(a) Load/unload force through y^+

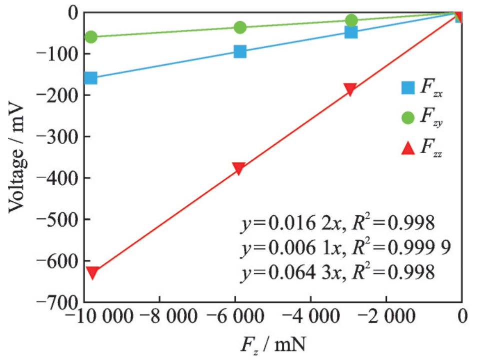


(b) Load/unload force through y^-

Fig.9 Sensor characteristic of y axis



(a) Load/unload force through z^+



(b) Load/unload force through z^-

Fig.10 Sensor characteristic of z axis

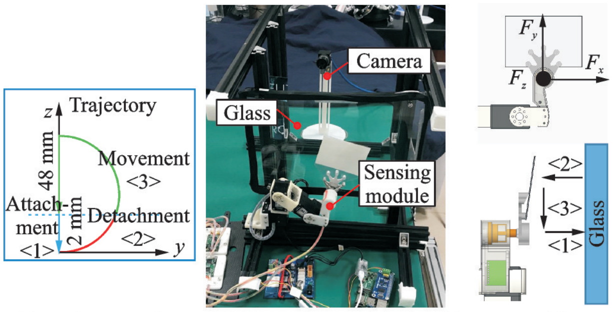
Table 2 Sensor performance parameters

Force	Sensitivity	Hysteresis error/%	Nonlinearity/%	Accuracy/%	Resolution ratio/%
F_x	0.585	0.05	0.09	1.25	0.74
F_y	0.557	0.44	0.23	2.49	0.80
F_z	0.255	0.06	0.04	1.81	0.64

3 Attachment Performance Experiments with Force Sensing Module

3.1 Experimental platform setup

The stress on the foot-end of the adhesive wall-climbing robot in the process of attachment and detachment has a very important impact on the stable movement of the robot. The proposed three-axis force sensor design can effectively sense the stress on the foot-end. With one limb of the three-axis force sensor for research of attachment performance, we set up a single limb attachment performance test platform. The platform is mainly composed of a contact area test base, a robot single limb with a three-axis force sensor and high-speed camera (Fig.11). The contact area test base is a synthetic glass surrounded by light strip, according to the principle of frustrated total reflection. When the light shoots into contact surface parallelly, contact with the basal part of the paddle can produce the bright spot. The single-limb equipped with a three-axis force sensor is placed on one side of the plexiglass plate. When the pad contacts with the plexiglass plate, the built-in force sensor can sense and collect the three-dimensional reaction force on the foot in real-time. The optical axis of the high-speed camera is placed perpendicular to the glass surface on the opposite side of the single-limb to record the image information during the pad contacting the substrate.



(a) Trajectory of robot's foot end (b) Experimental device (c) Foot-end frame

Fig.11 Experimental platform

3.2 Experiment results and discussion

In Fig.12, we can get the relationship between the preloading depth and the preloading pressure (reaction force): The greater the preloading depth, the greater the preloading pressure, which is consistent with the actual situation.

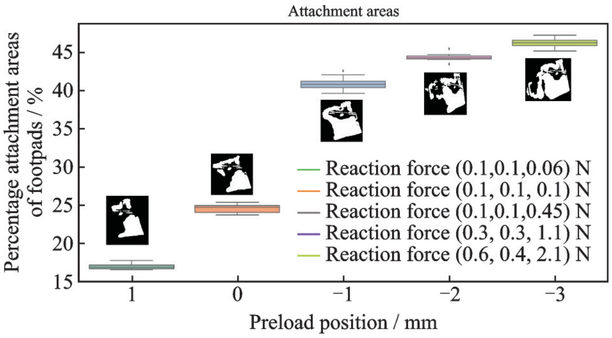


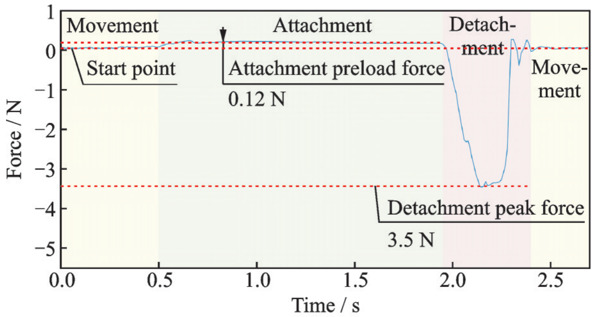
Fig.12 Attachment areas and percentage of footpads

As shown in Fig.12, the greater the preloading depth, the greater the adhesive area. It can be known from previous studies that the greater the pre-pressure is, the larger the adhesive area will be. The same conclusion can be drawn in combination with Figs.12, 13, which proves the effectiveness of the force sensor.

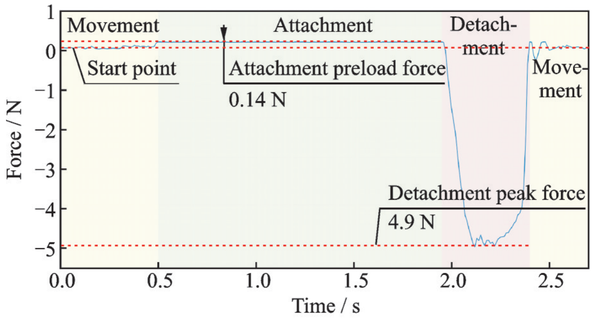
Besides, it can be seen from Fig.13, the adhesive areas decrease when preloading depth reaches to 3 mm.In general, it is not a good idea to improve the adhesive ability by increasing the preload force blindly, the foot-end reaction force experiment provides a reliable data basis for the motion control of the adhesive foot climbing robot.

4 Conclusions

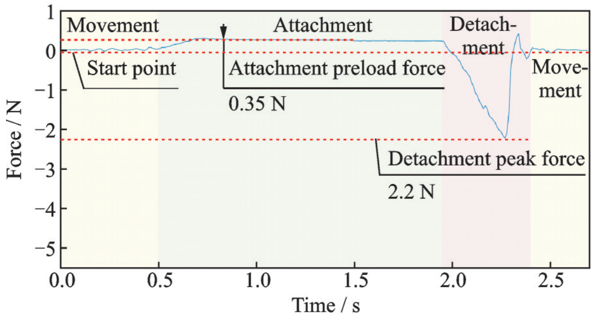
Aiming at sensing the interaction force for adhesive legged-climbing robot, a new type of three-axis force sensing module is designed. Force-sensing principle for the sensor is analyzed and verified based on ANSYS. Based on the results of the calibration experiment, the relationship between the voltage values and force is set up. The experiment results show that the designed three-axis force sensing module can meet the requirements of measuring adhesive legged-climbing robots. The following work will be focused on applying this three-axis force sensing module to an adhesive legged-climbing robot platform, and realize stably attaching and com-



(a) Reaction force through x axis



(b) Reaction force through y axis



(c) Reaction force through z axis

Fig.13 Attachment areas and percentage of foot pad

pliantly detaching. This study lays a foundation for realizing more complex robot motion control.

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Author contributions Prof. **DAI Zhendong** contributed to the design of this study. Mr. **GU Yu** and Mr. **DUAN Jinjun** designed the sensing module and experiments. Mr. **BIAN Qingyao** helped to set up the platform and parts of coding works. Mr. **WANG Bingcheng** and Mr. **WANG Liuwei** helped to finish certain mechanical and electrical works. Mr. **SONG Yi** gave some suggestions about sensor using. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

(Production Editor: ZHANG Bei)

仿壁虎机器人足端三维力感知模块研制

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摘　要：针对仿壁虎机器人运动控制中存在的黏附失效与脱附冲击问题，提出了一种具有高实时性能、传感/支撑一体化的足端三维力感知模块以提升机器人在非结构环境下的稳定运动性能。首先，通过有限元分析确定了由“马其他十字”与“双悬臂梁”结合的组合式结构；其次，基于实时操作系统设计交互式采集/传输系统实现了对足端三维力数据的实时采集和获取；接着，搭建标定平台并完成了对足端三维力感知模块的标定、解耦及测试；最后，基于该感知模块，实现了对仿壁虎机器人单腿黏附控制。实验结果表明，该足端三维力感知模块不仅可以支撑机器人自身重量，还实时采集足端黏/脱附力，为指导机器人稳定黏附与柔顺脱附打下硬件基础。

关键字：足端力感知模块；实时采集系统；黏/脱附力控制；仿壁虎机器人