The design of the force actuator used in extreme low temperature environment

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Abstract

The existing force actuators cannot work properly in the Antarctic under the condition of low temperature. In this paper, a new design scheme of force actuator is put forward. Combined with the actual situation and the requirement of thin mirror active optical experiment system, we design the force actuator structure which combined the active support and passive support, and use a s-shaped load-cell to realize the force feedback controlling. Passive support part is responsible for the adjustment of large travel with low precision, and active support part driven by PZT is responsible for the adjustment with high accuracy. Finally, test was carried out through the open loop and closed loop experiment in low temperature environment. The experimental results show that: The force actuator's output force is 120 ~ 280N, the accuracy is better than 0.05 N, meeting the requirement for the high precision under low temperature. The new kind of force actuator can be applied to the active optical support system in the Antarctic, and at the same time can also be applied to other structures of precision adjustment.

Keywords: force actuator, active support, passive support, low temperature environment， Piezoelectric ceramic

1. Introduction

Developing astronomical career in the Antarctic inland is a good opportunity for astronomy to surpass itself as soon as possible. Though the observatory site environment is very good, the development of the telescope is faced with a number of difficulties and key technologies, because of its harsh natural environment, such as low temperature, low pressure and limited outdoor working time. Active support in the low temperature and pressure environment is one of key techniques in construction of large diameter at the South Pole telescope project. It is irreplaceably important to solve this difficult problem. Force actuator is used as a component to adjust mirror surface deformation actively. The arrangement mode and number of force actuator will influence the capacity of mirror surface adjustment. It needs high accuracy and tiny change of output. It also needs to be stable when the external environment changed.

The usual structural style: (1)Electrical motor + counter weight + lever, such as Japanese 8M Subaru telescope, which realized actively support by moving the counter weight on the lever. (2)Electrical motor + ball screw + spring, like the force actuator used on 4.1M SOAR. (3) Pressure support, including hydraulic pressure and air pressure.

A new type of force actuator drove by PZT is put forward in this paper. In this design, counter weight is used as a passive

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adjustment and PZT drive is used as an actively high-accuracy adjustment. The advantage of this design is that it combines the large-stroke of counter weight and high-accuracy of PZT. This new type of force actuator is suitable for low temperature at the Antarctic inland. In the extreme low temperature environment, the common force actuators, which drove by stepping motor or hydraulic pressure, will lose their efficacy. The structure of force actuator drove by PZT combined with counter weight has great performance. Counter weight could adjust deformation caused by gravity when the wear parts (PZT) lose efficacy. So this structure has good system stability.

2. A new design of force actuator

2.1 The basic principle of PZT

PZT output micro displacement by using the converse piezoelectric effect. Piezoelectric ceramic pieces are cascaded and electrodes are paralleled in this structure. As shown in Figure 1, assuming that the displacement of a single layer with the thickness of t is Δt , so the displacement of n layers is Δl , $\Delta l = n \times \Delta t$

$$\Delta t = d_{33} \times V$$

$$\Delta l = n \times \Delta t = n \times d_{33} \times V = \frac{l}{t} \times d_{33} \times V = E \times d_{33} \times l$$

In the equation: V — impressed voltage;

d_{33} —Piezoelectric constant;

E— electric field intensity（V/t）;

L —the total length

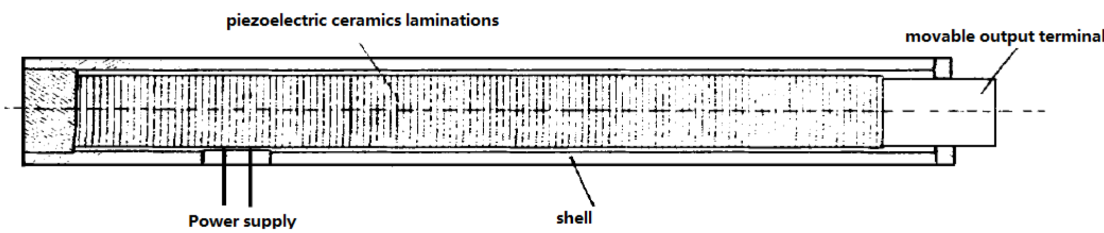

Fig. 1 PZT diagram

External thread encapsulated piezoelectric ceramic is used in the design. The product picture is shown in figure 2, and the parameters are shown in table 1.

Table 1 Parameters of the PZT

Type	Max/ Nominal displacement (μm)	Length L(mm)
FPSt150/7/80 M14	105/80	82

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Fig. 2 PZT product picture

2.2 Structure of the force actuator

On the premise of meeting the precision and stroke, the size and the overall quality of the actuator should be decreased as far as possible. The fine tuning device should be placed in the front of coarse adjustment device. The number of kinetic joints should be as few as possible so that friction could be limited to prevent friction from bring in too much error. The system adopts the force feedback closed loop control. The index of actuator is shown in table 2. Based on this idea, design of the actuator is shown in figure 3.

Table 2 Parameter requirements

Name	Technical index
Passive output force/N	120-280
Adjusting force/N	+/-50
Accuracy	1%

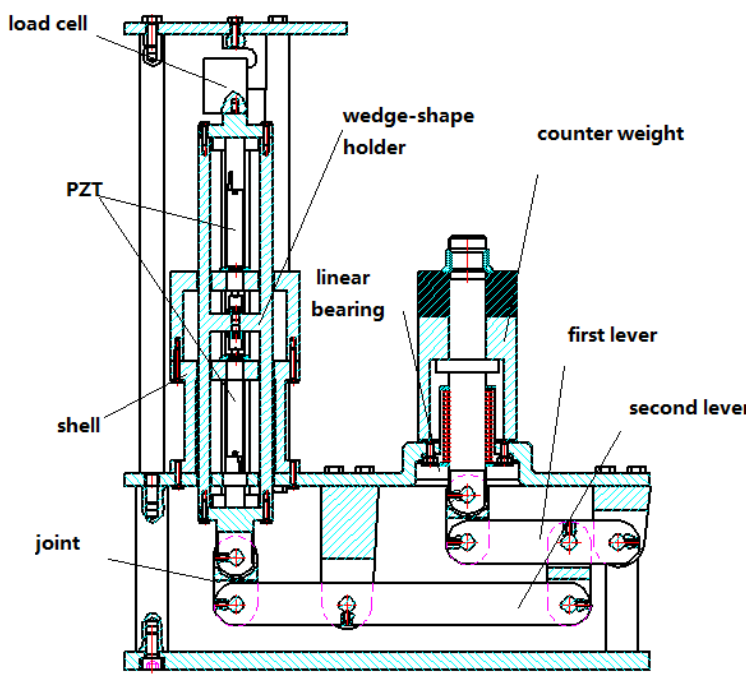

Fig. 3 Structure of the force actuator

2.3 Drive method

In order to achieve bidirectional force output, two piezoelectric ceramic actuators are used. Actuators are all fixed on the shell. One keeps zero displacement state while another one is working. Piezoelectric ceramics and wedge-shape support

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are connected by spring. In this way, the displacement output of PZT is translated into the force output of spring. Technical standard of the spring is GB/T 1972, whose inner diameter is 6.2mm. The active force output will be 134N when the displacement output of PZT achieve to maximum 0.08mm. The structure of drive method is shown in figure 4.

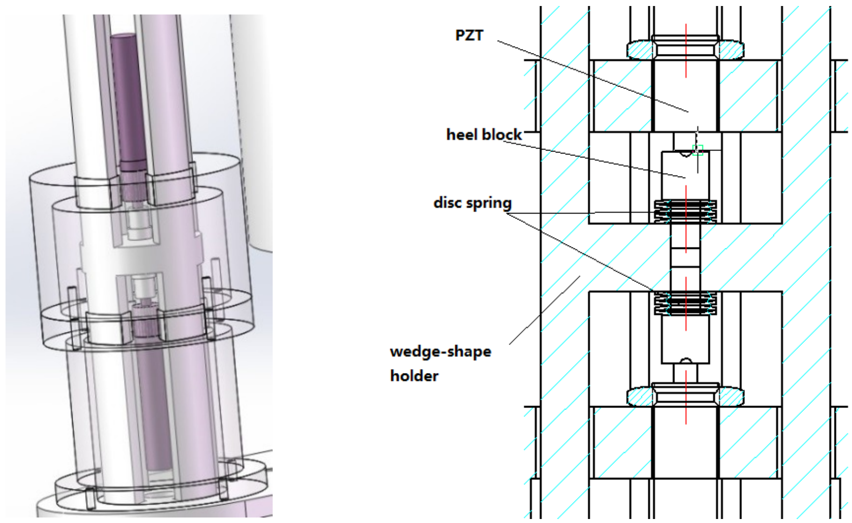

Fig. 4 Structure of the active support

2.4 The connecting joints

The wedge-shaped bracket and counter weight are connected by two levers. To decrease the error from friction and the deformation of levers, the joint structure applied on the lever fulcrum is designed. As shown in figure 5.

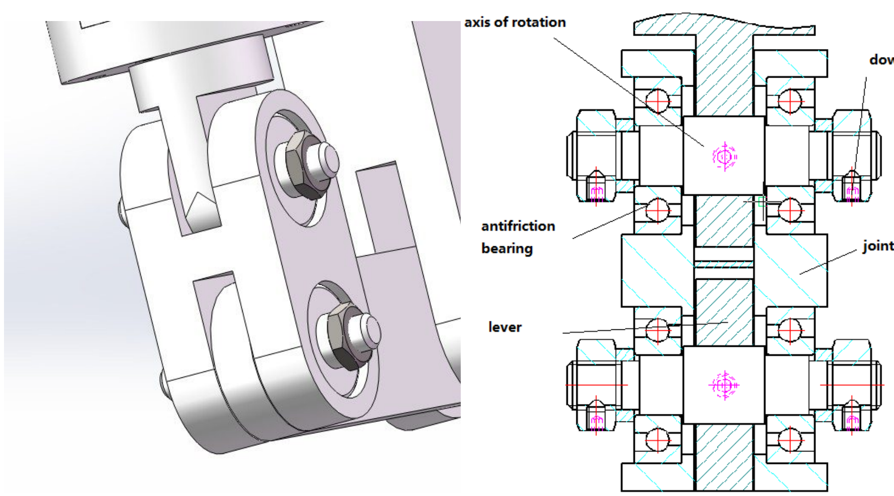

Fig. 5 Structure of the joint

Relative displacement will not occur between the lever and rotation axis. To decrease the friction between rotation axis and hole, the connecting joints and rotation axis are connected by rolling bearing. When the lever rotates, the deformation of levers could be avoided through the rotation of joints. The error is thus effectively reduced.

2.5 Force output of the passive support

To decrease the weight of counter weight and the overall dimensions of the actuator, the passive support is constituted by counter weight and two levers. The gravity of counter weight is enlarged and changed direction by leverage, and then load on the wedge-shape support. The counter weight is made up of thin metal sheet, with the gravity of

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45.9N(adjustable). The arm ratio of the first lever is 3:1, so the force loaded on the end of second lever is 140N. The arm ratio of the second lever is 2:1, so the force loaded on the wedge-shape holder is 280N. Because the passive support is mainly adjust the deformation of mirror caused by gravity, so the weight of counter weight should be adjusted according to the situation of actuator and the specific loading situation. The bearing bar is constrained by linear bearing so that it can only generate force perpendicular to the rack. When the telescope is working, the mirror is deflected the angle θ. The component force loaded on the lever from counter weight reduce to $45.9 \times \cos\theta$, while the axial compensation force which the mirror needs is changing by cosine law. Real-time passive compensation is thus come true in the process of the mirror movement. When the mirror rotates to the angle of 65°, the force output of the passive support is $280 \times \cos 65°$,about 119N.

3 Passive support static analysis

3.1 The influence of the horizontal deformation of levers

Due to the error of passive support part mainly comes from the deflection of the long lever, so the simulation analysis was carried out on the lever. When the gravity of mirror distributed on the region of the actuator is 280N, the horizontal maximum deformation of the second lever is 0.0081mm. At this time, the horizontal maximum deformation of the first lever is 0.0007mm. To compensate the deformation of mirror caused by gravity while the PZT is broken, the counter weight should be adjusted in this situation. So it can be considered as original state. To get the maximum error in the passive support part, we also need analysis the deformation of levers when the mirror rotates to ultimate position. At this time, the gravity distributed on the region of the actuator is 120N. The horizontal maximum deformation of the second lever is 0.0035mm, and the horizontal maximum deformation of the first lever is 0.0003mm. The perfect state and working state is shown in table 3 and table 4.

Table 3 Perfect state

	Force output/N	Counter weight/N	Arm ratio of the first lever
original state	280（Fixed）	45.9	122:40
ultimate state	120	45.9	122:40
	Deformation of the first lever /mm	Deformation of the second lever /mm	Arm ratio of the second lever
original state	0	0	180:90
ultimate state	0	0	180:90

Table 4 Working state

	Force output /N	Counter weight /N	Arm ratio of the first lever
original state	280（Fixed）	P（undetermined）	121.9993:40
ultimate state	F（undetermined）	P（undetermined）	121.9997:40
	Deformation of the first lever /mm	Deformation of the second lever /mm	Arm ratio of the second lever
original state	0.0007	0.0081	179.9919:90
ultimate state	0.0003	0.0035	179.9965:90

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The counter weight should be determined by gravity of the mirror. According to the lever theorem：

（1） First lever $P \times 121.9993 = f \times 40$

（2） Second lever $f \times 179.9919 = 280 \times 90$

P=45.904N

At the ultimate position, the mirror rotates to the angle of θ (cos θ =120/280). According to the lever theorem：

（1） First lever $P \times \cos\theta \times 121.9997 = f \times 40$

（2） Second lever $f \times 179.9965 = F \times 90$

F=120.0009N. The error is only 0.0009N.

3.2 The influence of the vertical deformation of levers

When the gravity of mirror distributed on the region of the actuator is 280N, the vertical maximum deformation of the second lever is 0.072mm, and the deformation of the first lever is 0.0032mm. When the gravity of mirror distributed on the region of the actuator becomes to 120N, the vertical deformation of the second lever is 0.031mm, and the deformation of the first lever is 0.0014mm.

The biggest impact from the vertical deformation of levers is that, when the levers bend, the force which originally should be vertically loaded on the bottom of the lever would produce an axial force component. It makes the actual force is less than the theoretical value.

First we calculate the error from the vertical deformation of levers when the force output is 280N.

The first lever: $\sin\theta = 0.031/82$.

Force loaded on the bottom of lever is $45.9 \times \cos\theta$

Assuming that the force loaded on fulcrum is f: $45.9 \times \cos\theta \times 122 \times \cos\theta = f \times 40$.

The second lever： $\sin\Phi = 0.072/180$.

Force loaded on the bottom of lever is $f \times \cos\Phi$.

$$f \times \cos\Phi \times 180 \times \cos\Phi = F \times 90$$

$$F = 6.1 \times M \times \cos 2\theta \times \cos 2\Phi \approx 280N$$

We can get the result: the error caused by deformation of vertical direction is almost zero.

When the force output is 120N, the deformation of vertical direction will be smaller. And the error can be ignored.

4 Control scheme of the actuator

PID is one of the earliest developed control scheme. More than 90% of control loop on the popular control board use the PID. The objective function set by classic PID parameters is in essence the overshoot, rise time, accommodation time. All these indexes influence each other, but we generally use the empirical method to find their best combining site. So it is hard to get a satisfactory result under the kinematics and dynamics parameters of time-varying. PID don't need accurate mathematical model of control system, and its control algorithm is simple and easy to realize. Classic PID control strategy is used to control the system. The structure of control system is shown in Figure 6 and Figure 7.

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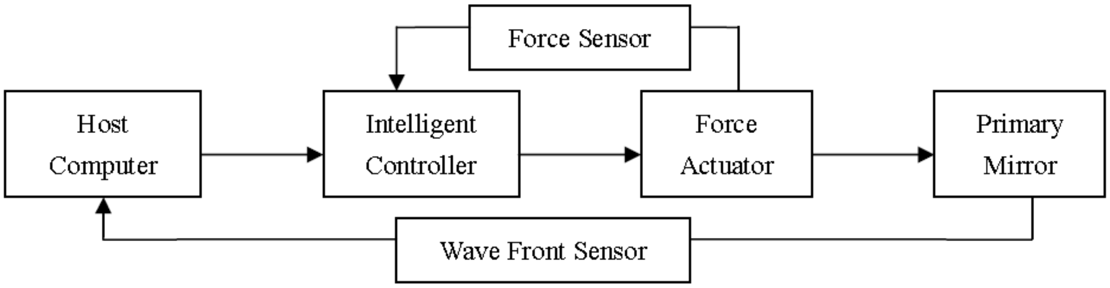

Fig. 6 Active optical control system structure

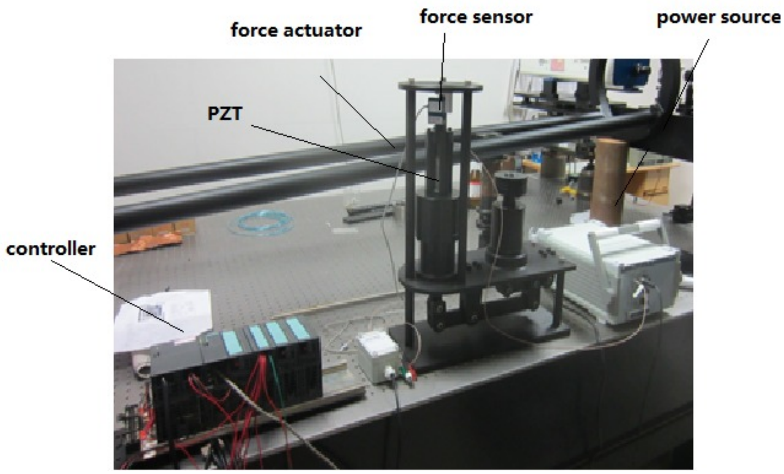

Fig. 7 Active optical control system experiment

In order to meet the needs of the actual requirements, the force actuator needs good open loop characteristics and output with stability and great accuracy. So the designed actuator should be tested, including open loop and closed loop testing. The force output along with the change of voltage is shown in the figure 8. The figure on the left shows the force output when the first PZT is working, and the right one shows the state when the second PZT is working. X-coordinate is the input voltage, while y-coordinate is the output force. It can be seen that the system has good linearity.

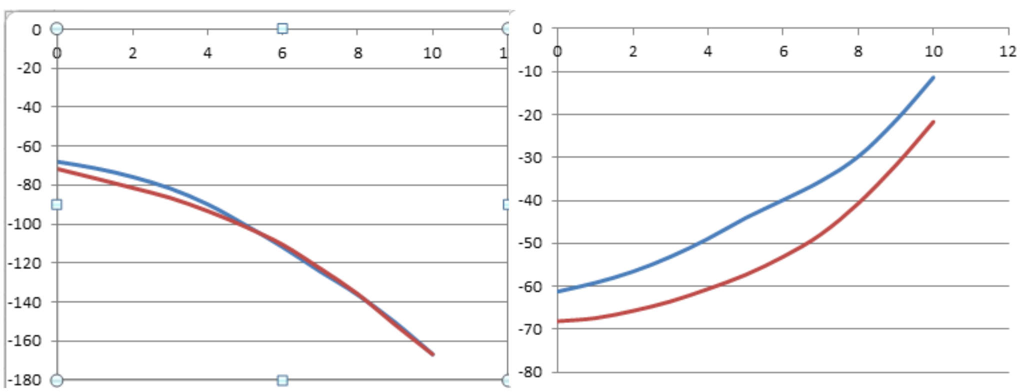

Fig.8 Open loop test

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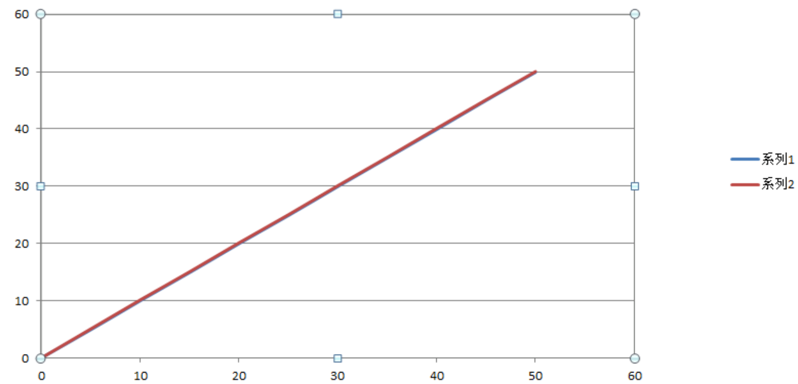

Fig.9 Close loop test

The experimental data of closed-loop control is shown the figure 9. The upper deviation curve and the lower deviation curve are almost coincident with the theoretical curve. Experiments show that the maximum error is less than 0.1N, and the response frequency is greater than 1 HZ.

5. CONCLUSION

A new kind of force actuator drove by PZT which combined active support with passive support is designed in this paper. Through the simulate analysis and theoretical calculation, the error of passive support can be almost ignored. When the active force output is in the range of -50N~+50N, the accuracy can achieve 0.05%, and the frequency of PID control can be greater than 1HZ. Because of the good stability of the components, this force actuator could be used in extreme low temperature environment.

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