Design and Practice Multi-channel Real Time System on Deformation Control of Optical Plate

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ABSTRACT

Optical plates (OP) play more and more important role in modern ground-based telescopes. They can be as segments composing primary mirror, deformable mirror for correcting air turbulence or active stressed lap used in polishing large aspherical optics. When control the deformation of these plates, we always confronts with common situations: high shape precision requirement, rapid deformation frequency with real time demand, intrinsic multi-channel coupling characteristic. So how to improve OP deformation performance becomes a critical task in practical design. In this paper, the control principle of OP is first introduced. Then a three-layer control architecture is presented. They are application layer, real time control layer and motion execution layer. After that we designed a prototype system following this framework, targeting active stressed polishing lap which has twelve motion channels. Both the hardware and software development are discussed thereafter. OP surface deformation experiments are carried out and surface shape obtained using LVDT array. Results verify the effectiveness of the design. And we are looking forward to use this control design in more channel and time demanding applications.

Key words: optical plate, deformation control, real time, MIMO system

1. Introduction

The study the most compelling areas in astrophysics as dark matter and dark energy, growth structure of the universe and characterization of extra-solar planets, etc. needs 30~50 meter class ground based telescope. Therefore construction of next generation giant telescopes is put on agenda. They are Thirty Meter Telescope [1] and Giant Magellan Telescope [2] leaded by US, European Extremely Large Telescope [3] and Chinese Future Giant Telescope [4]. To boost them from blueprint into reality, many advanced technologies are applied in these large projects. Among them there are three special one.

The first is active optics. Historically the large primary reflector had to be very thick to hold its shape to the required accuracy as telescope travelled across the sky. This limited their maximum diameter to 5 or 6 meter, such as Palomar Observatory's Hale telescope. Since 1990s a very thin mirror design is used, which is too thin to keep them rigidly in correct shape. With the help of an array of actuators behind, the mirror keeps an optimal shape, see in Figure 1a. This thin mirror with active actuators design is called active optics which changes shape of primary mirror to prevent deformation due to external influences such as wind, temperature and mechanical stress.

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The second is adaptive optics. When light form a star or another astronomical object enters the Earth's atmosphere, air turbulence, introduced by different temperature layers and different wind speeds, can distort and move the image. Images produced by any telescopes larger than a few meters are blurred by these distortions. Adaptive optics system tries to correct these distortions using a deformable mirror (DM) that lies in optical path. DM is an ultra-thin reflecting shell whose shape can be change rapidly, as showed in Figure 1b. Typically, DM is associated with hundreds mechanical actuators on backside each provides one degree freedom.

The third one is Active stressed polish lap (ASPL). Rigid passive lap cannot maintain an accurate fit to aspherical surface because of variations in curvature across the optical surface [5]. ASPL made the breakthrough by actively changing its shape as it moved over surface. So ASPL could share the benefit of high material removal rate, natural smoothing over a wide range of spatial frequencies and polishing highly aspherical optics directly. All advantages come from a set of actuators distributed around the lap edge which apply bending and twisting moments.

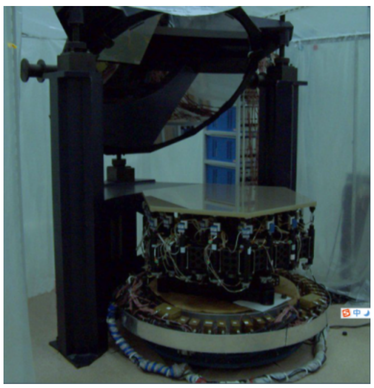

Figure 1a LAMOST Segmented Schmidt Plate with Active Optics [6]

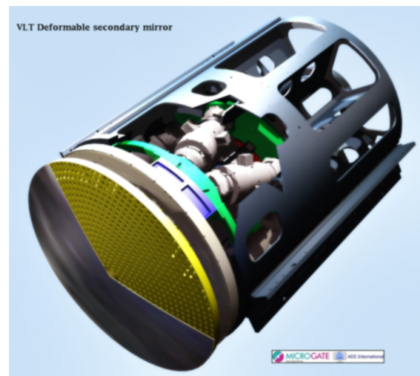

Figure 1b VLT Adaptive Optics using Deformable Secondary Mirror [7]

There is an important characteristic that active optics, adaptive optics and ASPL share in common. The critical part of three technologies is a flexible optical plate (OP). Whatever they are made of (Zerodur or Aluminum), one side of OP is working surface. It will correct aberrations in optical system or compensate the misfit on mirror. The other side is driving surface, equipped with tens or hundreds of actuators to deform OP to desired shape. Usually the OP precision plays a determinant role in the performance of above technologies.

When we control the deformation of OP, we always confronts with same situations: high shape precision requirement, rapid deformation frequency with real time demand, intrinsic multi-channel coupling characteristic. So how to improve OP deformation performance becomes a major task in practical design. In this paper, the control principle of OP is first introduced. Then a three-layer control architecture is presented. They are application layer, real time control layer and motion execution layer. After that we designed a prototype system following this framework, targeting active stressed lap which has twelve motion channels. Both the hardware and software development are discussed thereafter. OP surface deformation experiments are carried out and surface shape obtained using LVDT array. Results verify the effectiveness of the design.

2. Control Principle of Optical Plate

2.1 Optical Plate Control Requirement Analysis

(A) Multiple Input & Multiple Output (MIMO) Control Structure

The control of OP is a typical MIMO problem. As showed in Figure 2, the whole working surface is the output which can be divided into many small parts according to needs. The inputs are actuators on the driving surface to deform OP.

Every actuator provides one freedom degree. To get the ability of correcting high spatial frequency error and to meet the need of enlarging OP area, the number of actuator increases. This tendency can be seen in Table 1.

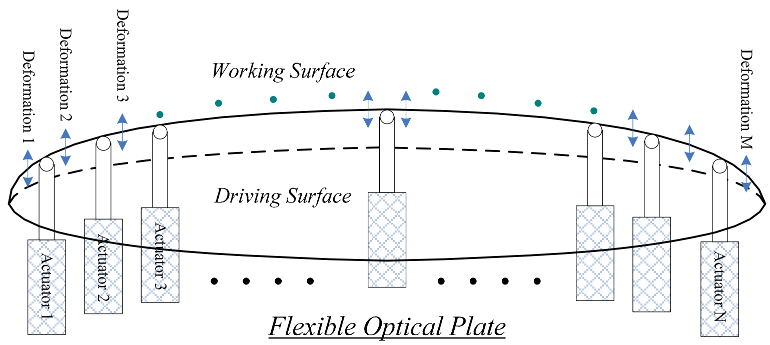

Figure 2 Input actuators and output deformation of optical plate

Table 1. OP Area and Actuators Number in Active Optics

Optical Plate	KECK Primary	VLT Primary	LAMOST Schmidt Plate	TMT Primary	EELT Primary
Optical Area (m^2)	75.76	52.78	18.86	662.65	1089.76
Actuator Number	108	150	888	1476	2394

(B) High Shape Precision Demand

In active optics and adaptive optics, OP compensates the aberration introduced by gravity, temperature or air turbulence. The typical surface error allowed is tens of nanometer. For active stressed lap, the requirement is less than 3 microns. How to achieve this high shape precision gives a big challenge to actuator (involving motors, mechanical transmitting structure and feedback sensors).

(C) High Deformation Frequency Requirement

Since gravitation and temperature change slowly, the period deformation for active optics is long, usually several minutes. Yet air turbulence transforms rapidly and ASPL rotates quickly, adaptive optics and ASPL needs hundreds times deformation per second. Since optical plate is an elastic body, all actuators are interconnected together. They need to be synchronized so strictly to provide satisfied performance.

(D) High Computational Ability Requirement

There is lots of computation work to do for controlling OP. After the sensor tested the deviation between ideal shape and current OP shape, a deformation map is calculated by pre-processing. Then each actuator command is achieved by executing special controlling algorithm which involves large amount computation. At last, each actuator operates its own PID control need additional calculation. Meanwhile all work should to be finished in a determined time slot to give real-time characteristic.

2.2 Mathematical Model of Optical Plate

For optical system, the gradient of deformation on OP is small, usually less than 100 microns/10mm. So the stress loaded by actuator is below material elastic limit. And OP is regarded as a perfect elastic body. Under this condition, the linear relation between deformation and forces can be applied to optical plate. For convenience of analysis, working surface is separated into m divisions. Each division outputs one deformation. On driving surface, the number of distributed actuator set to be n.

We can write the linear relation as following expression:

$$\begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_m \end{bmatrix} = \begin{bmatrix} k_{11} & k_{12} & \dots & k_{1n} \\ k_{21} & k_{22} & \cdots & k_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ k_{m1} & k_{m2} & \dots & k_{mn} \end{bmatrix} \cdot \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_n \end{bmatrix} + \begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_n \end{bmatrix} \tag{2-1}$$

Where $a_1, a_2, \dots, a_n$ are the forces applied on OP by actuators.
$d_1, d_2, \dots, d_m$ represent the desired deformation on OP working surface.
$e_1, e_2, \dots, e_m$ represent the residual error between achieved shape and desired shape.
$\{k_{ij} | i = 1 \dots m,\ j = 1 \dots n\}$ is the stiffness matrix that records constant elastic coefficients.

It can also be written into a concise form:

$$\mathrm{D} = \mathrm{K} \cdot \mathrm{A} + \mathrm{E} \tag{2-2}$$

Desired deformation is known, because we tested the optical aberration by sensors like Hartmann-Shark wavefront sensor or we know the misfit to fill. For stiffness matrix K, it can be obtained by either by establishing the finite element model of OP using elastic mechanics to calculate all coefficients or by input-output identification method to settle it. The problem left for us is calculating appropriate forces to minimize the residual error.

2.3 Actuator Force Calculation Algorithm

(A) Using least square method to obtain deformation forces

The most manifest solution to above problem is least square (LS) method. Its aim can be expressed as:

$$\mathrm{Min}\{(K \cdot A - D)^T (K \cdot A - D)\} \tag{2-3}$$

And the LS solution is:

$$\mathrm{A} = (K^T K)^{-1} K^T D \tag{2-4}$$

The advantage of LS solution is it provides minimum sum of residual error squared and needs very small amount of calculation. Due to mechanical and electrical restriction, each actuator usually yields limited range of force. The main drawback of LS method is it could not regulate output forces range and in most circumstances force range may exceed the capability of actuator so much that it couldn't be executed in practice.

(B) Using damp least square method to obtain deformation forces

So some improvement should be done to constrain forces to an acceptable range meanwhile fit precision should also be guaranteed. Fortunately, the damp least square method (DLS) (Levenberg 1944) can provide such a solution. It has also been used in active optics in LAMOST successfully [8]. The aim of DLS method is:

$$\mathrm{Min}\{(K \cdot A - D)^T (K \cdot A - D) + p(A^T A)\} \tag{2-5}$$

And the DLS solution is:

$$\mathrm{A} = (K^T K + pI)^{-1} K^T D \tag{2-6}$$

Here '*p*' is a positive number called damp factor and '*I*' is a unit matrix. The key to understand DLS method is damp factor '*p*'. When a bigger the damp factor is selected, the force range may reduce a bit but residual error may increase a little. Two extreme conditions may help to explain this tendency more clearly. If we set damp factor to zero, DLS method degrade into LS method which has highest precision but greatest force range. Otherwise if damp factor is infinite, force range tends to be zero and we get worst fit precision.

3. Control System Study of Optical Plate Deformation

3.1 Control System Architecture Design

To fit the MIMO control structure and meet the need of high shape precision, high deformation frequency and high computation ability, a three-layer control architecture is presented, as showed in Figure 3. They are application layer (top layer), real-time control layer (middle layer) and motion implementation layer (bottom layer).

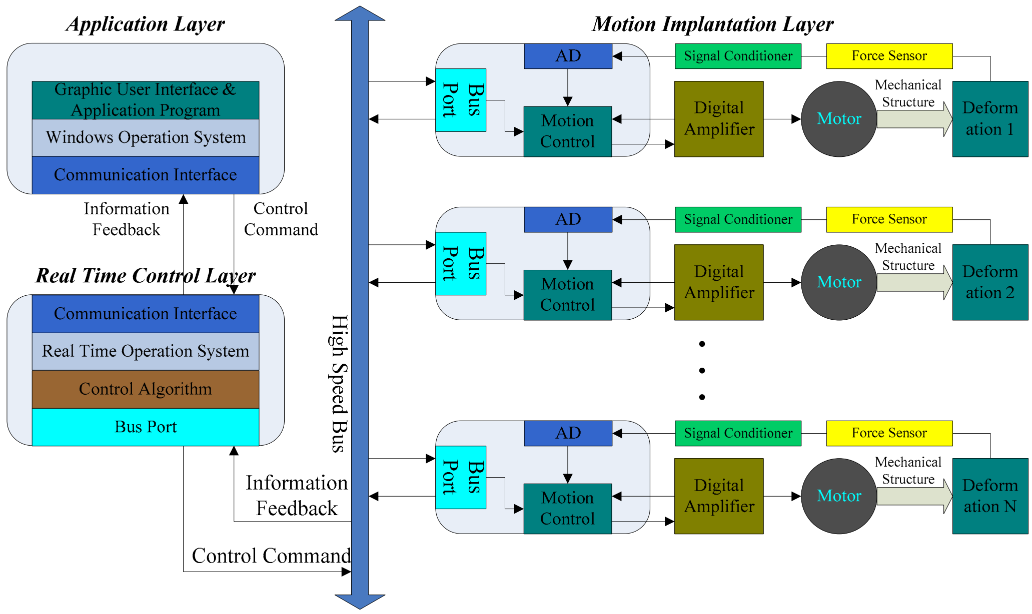

Figure3. Control system architecture of OP

(A) Application Layer (AL)

It is constructed on PC platform and runs Windows or Linux OS. This prevalent configuration could accommodate various selections of accessory and lower the technical doorsill for operator. Software is developed by general integrated development environment to provide graphic user interface and application program. It is also a platform to develop and debug programs on real-time control layer. When system runs, it displays current OP information, such as actuator feedback, following error. At the same time, host software sends command to middle layer by communication interface.

(B) Real Time Control Layer (RTCL)

It is central part of the system. Constructed on reliable hardware and run real-time OS, it provides high stability and small time jitter. To execute large dimension matrix algorithm like DLS, strong CPU is indispensable. It also needs a high speed bus interface to give flexibility and expansibility to meet different configuration. The main work of middle layer is to calculate algorithm and transmit control command to motion implementation layer. Meanwhile it interprets commands from application layer. The use of real-time OS guarantees the synchronization among actuators.

(C) Motion Execution Layer (MEL)

This part is responsible for actuator control. Received command from middle layer by data bus, it uses embedded microcontroller to construct control loop: reading feedback signal with high resolution AD convertor, comparing with command, using PID method, exporting signal to amplifier to drive the motor, getting the deformation. It also report actuator status to up layers.

This control architecture offers many characteristics, such as high openness, expansibility and flexibility.

4. Demonstration on Active Stressed Polishing Lap

4.1 ASPL Mechanical Arrangement

The deformable part of stressed lap is a circular aluminum plate. There are twelve steel tubes around the plate. Actuators create bending and twisting moments at the edge of the plate by applying forces to the top of the tubes. Figure 4a shows a schematic side view of such actuator. The mechanical components of an actuator consist of a torque motor, ball screw, lever arm, and tight wire. The tension in each wire is measured with a load cell at the termination point, and this tension serves as the feedback signal. Three actuators compose a group and are arranged to form an equilateral triangle, as showed in Figure 4b.

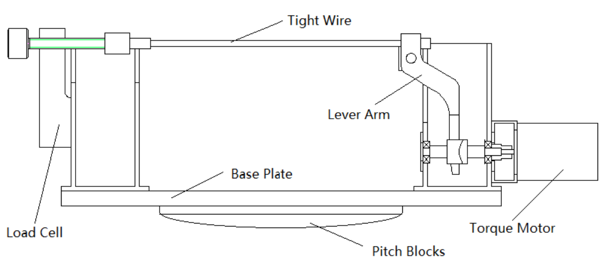

Figure 4a Side schematic of single actuator in ASPL

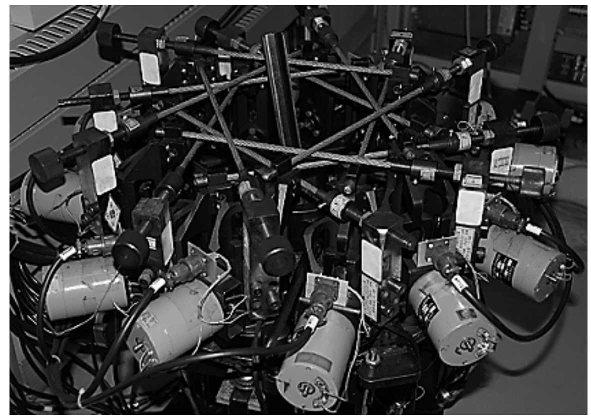

Figure 4b ASPL with twelve actuators on test be d

4.2 ASPL Control Configuration

Three-layer control architecture described in chapter 3 is applied for ASPL.

(A) Electrical Hardware Layout

In application layer, a PC platform is used for calculating aspherical misfit, download control file to real-time control layer, showing actuator feedback following error. It connected to RTCL by 100M Ethernet. RTCL is constructed on a rugged chassis. The central processor is 1.73GHz quad-core Intel i7-823 CPU running ETS real-time OS (Ardence Company) which could yield sufficient computation ability and stability. It transfers commands to MEL and receives information from MEL via high speed PCI-e 2.0 bus. In MEL, DSP is responsible for specific actuator control. A 16bit ADC reads the feedback signal conditioned by isolation amplifier and a 16bit DAC is used to control motor driver.

(B) Control Software Design

During operation, RTCL runs two threads. One with higher priority reads polishing machine encoders and updates force commands at a rate of 100Hz. The other takes care of Ethernet communication. A force command is issued to an actuator by placing the data onto PXI-e bus that is connected to all actuators. MEL continually reads the load cell feedback and compares it with receiving command and runs PID control loop at 4 KHz.

4.3 ASPL Experiment

(A) Single Actuator Testing

The first stage experiments are carried out for single actuator to test its performance and optimize control parameters. Since actuators are same in both mechanical structure and electrical configuration, the results can be applied for all. Test one uses step signal to get the step response of actuator. The height of step signal is 10 Newton and record length is 1 second. Seven curves are obtained by using different PID parameter and results are showed in Figure 5a. The proportional gain is 10, 20, 40, 80, 160, 320 and 640 respectively. For convenience, we keep the integral and differential gain unchanged. There is large amount of overshot when P gain is small and the rising time is long. With the increasing gain step by step to 160, we got the smaller overshot, shorter rising time and settle time. When P gain is greater than 320, the curve vibrates and system becomes unstable. So we select P gain to 160 which yields 180ms rising time and 2% overshot.

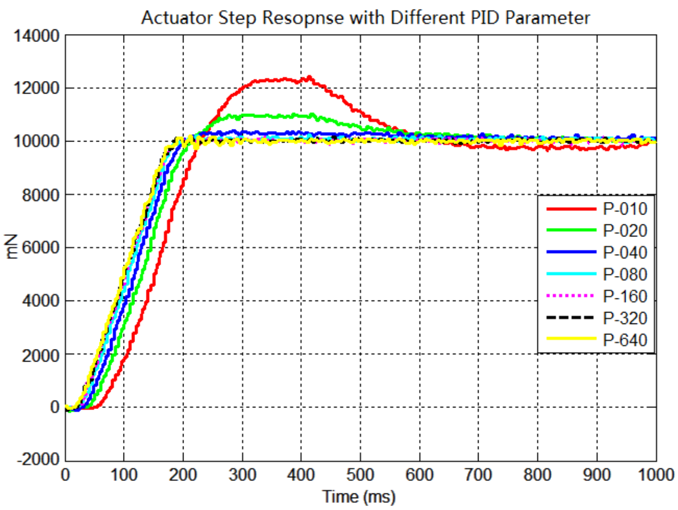

Figure 5a Step Response with Different PID Parameter

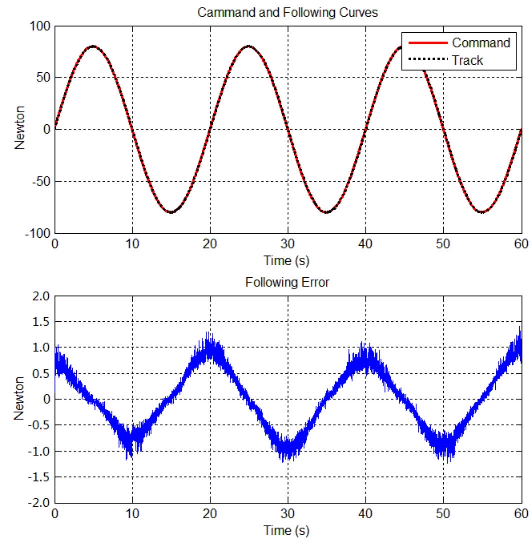

Figure 5b Actuator Following Sine Wave

Test two uses sine wave signal to test tracking ability of actuator. The signal period is 20 seconds and its amplitude is 160 Newton (ASPL's typical working condition). Test result is recorded in Figure 5b. Top graph shows the command curve which is ideal sine wave in one minute and the real actuator following curve. The two curves are so close to each other that cannot be separated apart. The bottom graph shows the following error (error RMS value is 0.57 Newton).

(B) Multiple Actuators Testing

The second stage experiments are carried out for all twelve actuators to do more comprehensive evaluation. We still use 20 seconds sine wave (altitude 160 Newton) to test. Twelve actuators follow twelve sine curves. Yet there is a 0.15π phase shift between consecutive actuators. Since ASPL maximum rotating speed is 3RPM, the 20 seconds period is quick enough to simulate this situation. The maximum force actuator applied is 160N. This altitude is also large enough and all actuators work simultaneously. So this comprehensive test creates the most severe working condition for ASPL.

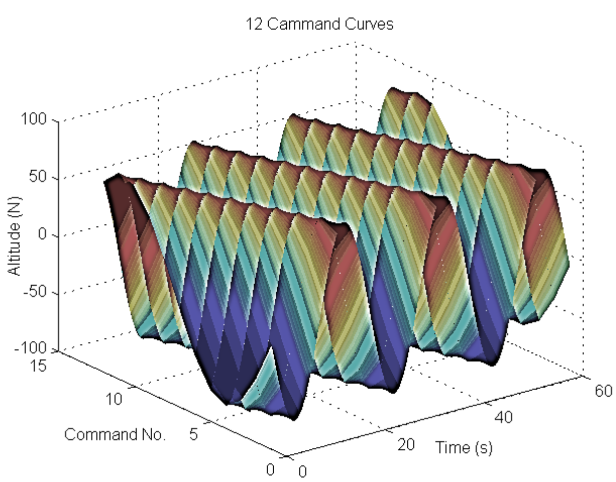

Figure 6a Twelve Actuators Sine Commands

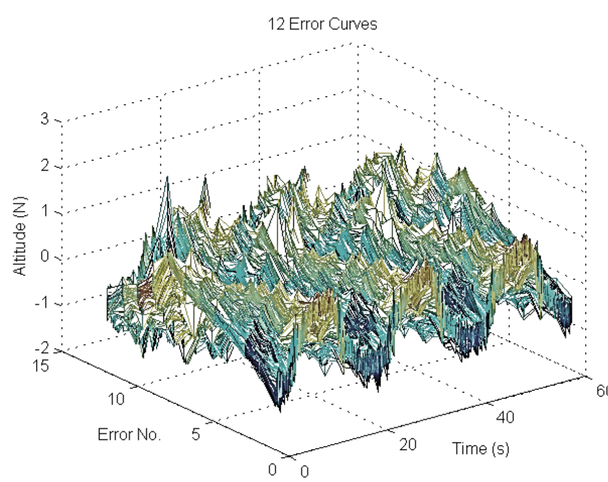

Figure 6b Twelve Actuators Following Error

The right figure shows twelve command sequences. They are sine curves with different initial phase. The time span is 60 seconds. The left is following error for twelve actuators with the same time span. The following error RMS for all actuator is 0.52 Newton.

(C) Surface Precision Calibration

The third stage experiments are carried by adding linear variable differential transformer (LVDT). Sixteen LVDT make up a 4×4 square array to test array. Each LVDT holds 2mm range and could provide 1 micron precision. Experiments show that lap surface repeatability is 2.4 microns which is acceptable for polishing needs.

5. Conclusions

In construction modern large aperture optical telescope, a kind of flexible optical plate plays more and more important role. They can be as segments composing primary mirror, deformable mirror for correcting air turbulence or active stressed lap used in polishing large aspherical optics. When control the deformation of these plates, we always confronts with common situations: high shape precision requirement, rapid deformation frequency with real time demand, intrinsic multi-channel coupling characteristic. So how to improve OP deformation performance becomes a critical task in practical design. This paper first introduces the principle of OP control. Then a three-layer control architecture is presented. They are application layer, real time control layer and motion execution layer. After that we designed a prototype system following this framework, targeting active stressed polishing lap which has twelve motion channels. Both the hardware and software development are discussed thereafter. OP surface deformation experiments are carried out and surface shape obtained using LVDT array. Results verify the effectiveness of the design. And we are looking forward to use this control design in more channel and time demanding applications like adaptive optics.

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