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Rate control of tip-tilt mirror using position sensors for an image-based tracking loop

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Abstract. For an image-based tracking loop system of tip-tilt mirror, the traditional control methodologies mainly include a single-position loop or two-position loop. The most effective method for enhancing tracking performance is to increase control gain for a high bandwidth. However, the image sensor sampling rate and time delay engendered by data processing restricts the bandwidth. Therefore, a position-rate control method is proposed to improve the performance of a tip-tilt mirror control system. The angular rate of tip-tilt mirror is calculated from the angular position measured by the linear encoder. The open-loop rate transfer function of tip-tilt mirror features differential in the low-frequency domain because the original tip-tilt control system is zero-type. When the inner rate feedback loop is implemented, an integrator is introduced into the original position loop. A PI (proportional-integral) controller can stabilize the position loop such that two integrators are in the tracking loop, so the low-frequency performance can be improved compared to the original control method. The experimental results coincide with the theoretical analysis and then verify the correctness of the presented theories. [DOI: 10.1117/1.OE.59.1.017102]

Keywords: linear encoder; image sensor; position-rate control; time delay; error attenuation; tip-tilt mirror.

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1 Introduction

Image-based tip-tilt mirror tracking control systems are extensively utilized in space observation, space communication, target tracking, and other fields.[1–3] Thus, the closed-loop performance of the tip-tilt mirror control system is essential for high-precision positioning. There are two reasons for this: one is for rapid response and the other is for error attenuation, especially in the low-frequency domain. The previous studies on tip-tilt mirror control modes focus on only a position tracking loop, of which the feedback error signal is obtained from the image sensor such as a charge-coupled device (CCD).[4,5] A modified method is to increase a faster inner position loop to form a two-position control loop by using an eddy current sensor.[6,7] However, this method only increases the inner control loop bandwidth to facilitate the design of the outer tracking loop controller. In fact, the two-position control mode has no obvious improvement on error attenuation. Because the image sensor usually needs a relatively large amount of integral time for a high-definition image, the control bandwidth is restricted by time delay of the image sensor. To improve tracking accuracy and reduce the adverse effects of tracking delay, scholars have adopted a variety of optimization methods in terms of upgrading hardware and software architecture.[8] In CCD systems with sampling rates up to 5 KHZ, model reference control[9] may be a good way to further improve the control performance of tip-tilt mirrors. Predictive control[10,11] is considered to be an effective method for compensating time delay. However, since

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the predictive controller cannot predict white noise, it is only efficient in low measurement noise conditions. Accelerometers were investigated to implement acceleration feedback loop.[12] To avoid saturations quadratic integral, a bandpass filter is designed as an acceleration controller. Therefore, there is still a quadratic differential effect in the low-frequency range, so error attenuation in the low-frequency range cannot be improved. A sensor fusion framework named the closed-loop fusion was proposed, which fused the low-bandwidth sensor and high-bandwidth sensor.[13] Although it has yielded excellent results in the tip-tilt mirror target tracking system, the problem of compensating the direct-current drift and a random-walk effect of inertial sensors was not solved. Inertial sensors such as fiber optic gyroscopes are used to implement velocity feedback control.[14–16] The inertial sensor is a contact sensor, resulting in an extra load to restrict the response of the control system. However, linear encoders are nonintegral contact encoders, which are designed to be small and easily mounted. A linear encoder is a measurement feedback device that works with the optical principle of the grating. Compared with eddy current sensors and other noncontact sensors, linear encoders have high resolution up to 32 bits. Hence, a position-rate control method based on linear encoder is proposed to enhance the closed-loop performance of the tip-tilt mirror control system.

The remainder of the paper is organized as follows. Section 2 introduces image-based tip-tilt mirror tracking control system, include the structure of the system and the controller design in practical applications of the control loop. Section 3 presents the experimental results. Section 4 presents the discussion. Concluding remarks are presented in Sec. 5.

2 Tip-Tilt Mirror Control System

The configuration of an image-based tracking system for tip-tilt mirror is shown in Fig. 1, including tip-tilt mirror, image sensor, control unit, and driver. The driver actuates voice coil motors to achieve tracking target for the tip-tilt mirror. The controller is used to implement the control algorithm. The laser is used to simulate the target. The target information can be provided by the image sensor such as a CCD. The motion signal of the tip-tilt mirror can be obtained from sensors mounted on the tip-tilt mirror.

2.1 *Structure of Two-Position Control*

The traditional tip-tilt mirror control system with two-position loop is shown in Fig. 2. The feedback signal of the outer position loop is obtained from a CCD. The error signal of the inner loop is angular position signal, which provided by the linear encoder mounted on the tilt-tilt mirror. When the dual loop is achieved, the closed-loop transfer function can be given as follows:

$$G_{\text{close-p}}(s) = \frac{C_1(s)P(s)}{1 + C_1(s)P(s)}, \tag{1}$$

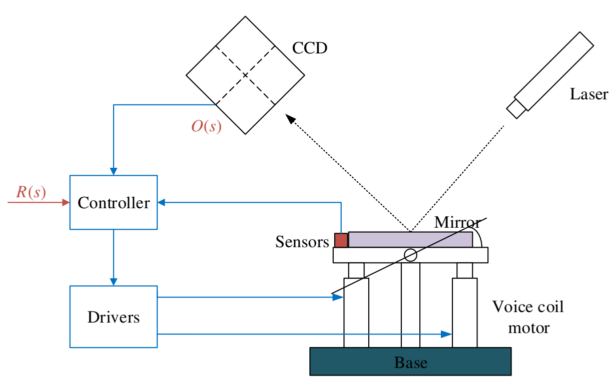

Fig. 1 Configuration of an image-based tracking control system for tip-tilt mirror.

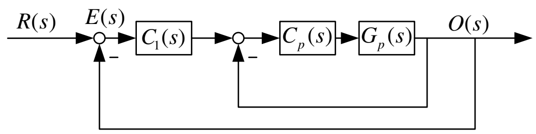

Fig. 2 Functional block diagrams of two-position control mode.

where the transfer function $P(s)$ called the inner position closed-loop transfer function is defined as follows:

$$P(s) = \frac{C_p(s)G_p(s)}{1 + C_p(s)G_p(s)}. \tag{2}$$

In fact, the outer position closed-loop bandwidth is inevitably limited by $P(s)$ and time delay of the CCD. The inner position loop sensor uses a linear encoder with a sampling frequency of 5 KHz, which is much faster than that the outer-loop CCD sensor of 500 Hz. The inner position closed loop can be obtained high bandwidth since it is not limited by sampling rate and time delay. Therefore, it is reasonable to approximate $P(s)$ equal to 1 to some extent below the closed-loop bandwidth. The time delay function $e^{-\tau s}$ can be used to describe the characteristics of the CCD.

A perfect controller $C(s) = K/s$ can be designed to stabilize the system. The open-loop transfer function with position inner loop can be expressed as follows:

$$G_{\text{open\_p}}(s) = C_1(s)e^{-\tau s} = \frac{K}{s}e^{-\tau s}. \tag{3}$$

The stability of a closed-loop system depends on the phase margin (PM) and gain margin (GM), which are subjected to PM $\geq \pi/4$ and GM ≥ 6 dB are usually specified. In this paper, we choose $\pi/4$ as PM and according to the definition of PM, we have

$$\begin{cases} \tau\omega_c = \pi/4 \\ K/\omega_c = 1 \end{cases}. \tag{4}$$

$K = \omega_c = \frac{\pi}{4\tau}$ can be easily derived. Thus, the integral controller $C_1(s) = \frac{\pi}{4\tau s}$, which depends on the time delay τ can stabilize the system. Therefore, we can easily get the error transfer function

$$E_p = \frac{1}{1 + C_1(s)e^{-\tau s}} = \frac{1}{1 + \pi/(4\tau s) \cdot e^{-\tau s}}. \tag{5}$$

The error transfer function shown in Eq. (5) shows that minimizing the line-of-sight error only depends on the outer position closed-loop bandwidth, which is inevitably limited by time delay of the CCD.

2.2 *Structure of Position-Rate Control*

For further improving the closed-loop performance, a rate feedback control is introduced to the tip-tilt mirror control system. The linear encoder has characteristics of high resolution and high precision. Therefore, the linear encoder can not only accurately measure the angle position of the mirror but also provide the angular rate by its differential.

The tracking control system with position-rate mode is described in Fig. 3. Compared with the two-position control mode in Fig. 2, an integral is introduced into the tracking control system. The closed-loop transfer function with position-rate control mode can be depicted as

$$G_{\text{close-v}}(s) = \frac{C_2(s)V(s)}{1 + C_2(s)V(s)/s}. \tag{6}$$

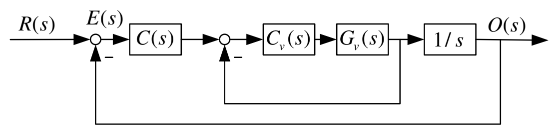

Fig. 3 Functional block diagrams of position-rate control mode.

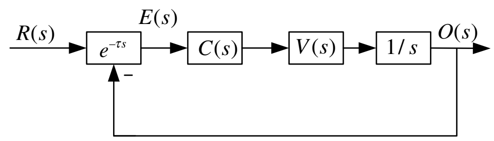

Fig. 4 Functional block diagrams of the time delay control system with position-rate control.

Similar to $P(s)$, the transfer function $V(s)$ called the rate closed-loop in inner loop is defined as follows:

$$V(s) = \frac{C_v(s)G_v(s)}{1 + C_v(s)G_v(s)}. \tag{7}$$

The tracking delay loop with rate feedback loop is shown in Fig. 4. When rate feedback closed-loop is implemented, $V(s) = 1$ is reasonable below the closed-loop bandwidth.

For this system, a PI controller can be used to stabilize the system. The open-loop transfer function is shown as

$$G_{\text{open\_v}}(s) = C_2(s)V(s)\frac{1}{s}e^{-\tau s} = \frac{K_P(K_I s + 1)}{s}\frac{1}{s}e^{-\tau s}, \tag{8}$$

where K_P and K_I are the parameters of PI controller. To make the feedback system robust, we choose $\pi/4$ as PM. According to the definition of PM, we have

$$\begin{cases} \text{arctg}(K_I \omega_c') - \tau\omega_c' = \pi/4 \\ K_P\sqrt{(K_I\omega_c')^2 + 1} = \omega_c'^2 \end{cases}. \tag{9}$$

From Eq. (9), the PI controller parameters $K_P = 0.071/\tau^2$ and $K_I = 7.1869\tau$ are easily derived. The error transfer function shown in Fig. 4 is given as

$$E_v = \frac{1}{1 + C_2(s)/se^{-\tau s}} = \frac{1}{1 + 0.071/\tau^2(7.1869\tau s + 1)/s^2 \cdot e^{-\tau s}}. \tag{10}$$

Compared with the original position control mode, two integrators are introduced into the control system.

2.3 *Performance Comparison*

Error attenuation is a key parameter to evaluate the performance of a closed-loop control system. To compare the error attenuation performance of the two control modes, the following equation can be obtained by combining Eqs. (5) and (10):

$$\left|\frac{E_p}{E_v}\right| = \left|\frac{1 + 0.071/\tau^2(7.1869\tau s + 1)/s^2 \cdot e^{-\tau s}}{1 + \pi/(4\tau s) \cdot e^{-\tau s}}\right|. \tag{11}$$

Let $20\ \lg|E_p/E_v| = 0$, which means that two control modes have same error attenuation performance. Thus, the result of $\omega = 0.1189/\tau$ can be solved to satisfy with this condition. When $\omega < 0.1189/\tau$, $20\ \lg|E1/E2| > 0$, it indicates that the error attenuation performance of the two-position control mode is worse than that of the position-rate control mode. When $0.1189/\tau < \omega < \pi/4\tau$, $-5\ \text{dB} < 20\ \lg|E1/E2| < 0$ is obvious, which illustrates that the error attenuation of the position-rate control mode is a bit lower than that of the two-position control mode in the middle frequency range. Thus, the position-rate control mode has better error attenuation performance overall.

3 Experimental Verification

The tip-tilt mirror is a two-axis system. This experiment focuses on one axis due to the symmetry of the two axes. The image-based tracking system experimental setup consists of tip-tilt mirror, laser, reflector, control unit, driver, and position-sensitive detector (PSD) (as shown in Fig. 5). In existing laboratory equipment, a PSD is implemented to simulate a CCD, which has sampling rate with 500 Hz, and the delay parameter τ is about 0.006 s, which is approximately three times more than the sampling interval of 0.002 s. The linear encoder mounted on the tip-tilt mirror [Fig. 6(b)], which is an absolute optical encoder with a resolution of 50 nm.

The Bode response of the tracking system with the two-position control loop and position-rate control loop is given in Fig. 6. When the magnitude reaches −3 dB, the frequency of the tracking control system with position-rate loop is slightly lower than that with two-position loop. This indicates that adopting rate feedback has a little lower closed-loop bandwidth. It is not harmful to the essentials, because the rate control mainly improves the error attenuation in the low-frequency domain.

Bode responses of two error transfer functions depicted in Eqs. (5) and (10) are shown in Fig. 7. When $\omega < 2.63$ Hz, the error attenuation performance of the two-position control mode is worse than that of the position-rate control mode. On the contrary, when $2.63\text{ Hz} < \omega < 25.3$ Hz, the two-position loop is better than position-rate loop. The position-rate control mode

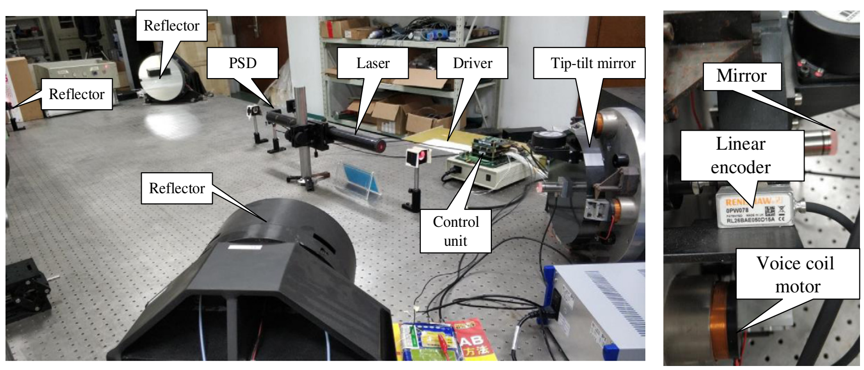

Fig. 5 Configuration of experimental platform: (a) global diagram and (b) local diagram of tip-tilt mirror.

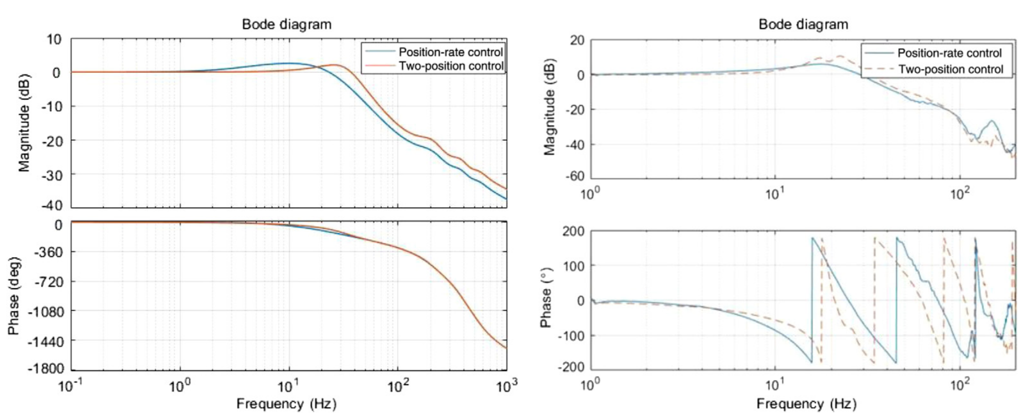

Fig. 6 Tracking control closed-loop responses of the tip-tilt mirror system: (a) simulation and (b) experiment.

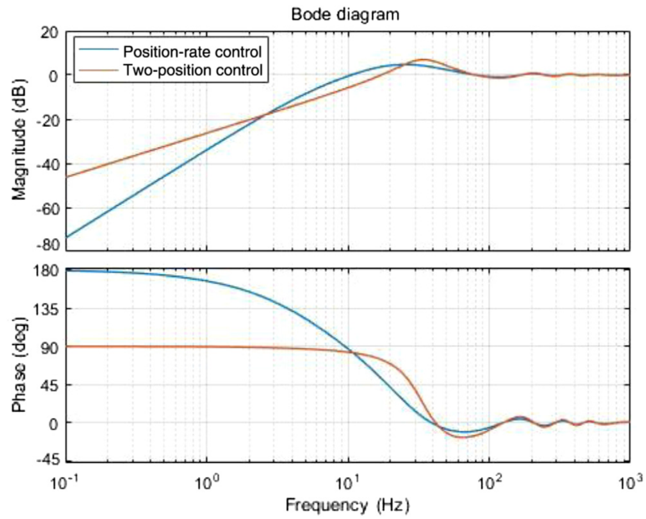

Fig. 7 Bode responses of two error transfer functions.

loses a bit error attenuation performance at the middle frequency range. It can be concluded that the tracking control system with position-rate control mode has better error attenuation performance than that with two-position control mode in the low-frequency range.

Experimental results show that the error attenuation bandwidth (about 7 Hz) in the position-rate control mode is lower than that in the two-position control mode (about 8 Hz) in Fig. 8. In the frequency range of about 2 to 9 Hz, the error attenuation performance for the two-position control mode is a little better. At the low-frequency range of about 1 Hz, the position-rate control mode performs better than the two-position loop. Although the experimental results do not fully match the theoretical analysis, the variation trend is consistent with the simulation results. In addition, experimental tests are conducted on frequency bands below 1 Hz, using sinusoidal signals with amplitude of 3000, with frequencies of 0.1, 0.5, and 1 Hz. The tracking error of experimental results and PSD noise are shown in Fig. 9.

In the experiment, due to the PSD noise, the error attenuation performance does not reach the results seen in the simulation analysis (see Table 1). However, the error attenuation has reached its limit in this case. It can still be proved that the control mode with the position-rate loop has better error attenuation performance than the control mode with two-position loop in the low-frequency range.

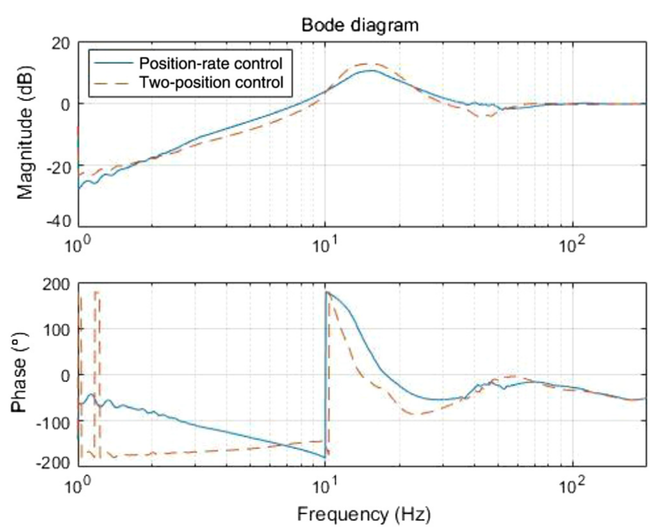

Fig. 8 Error attenuation responses.

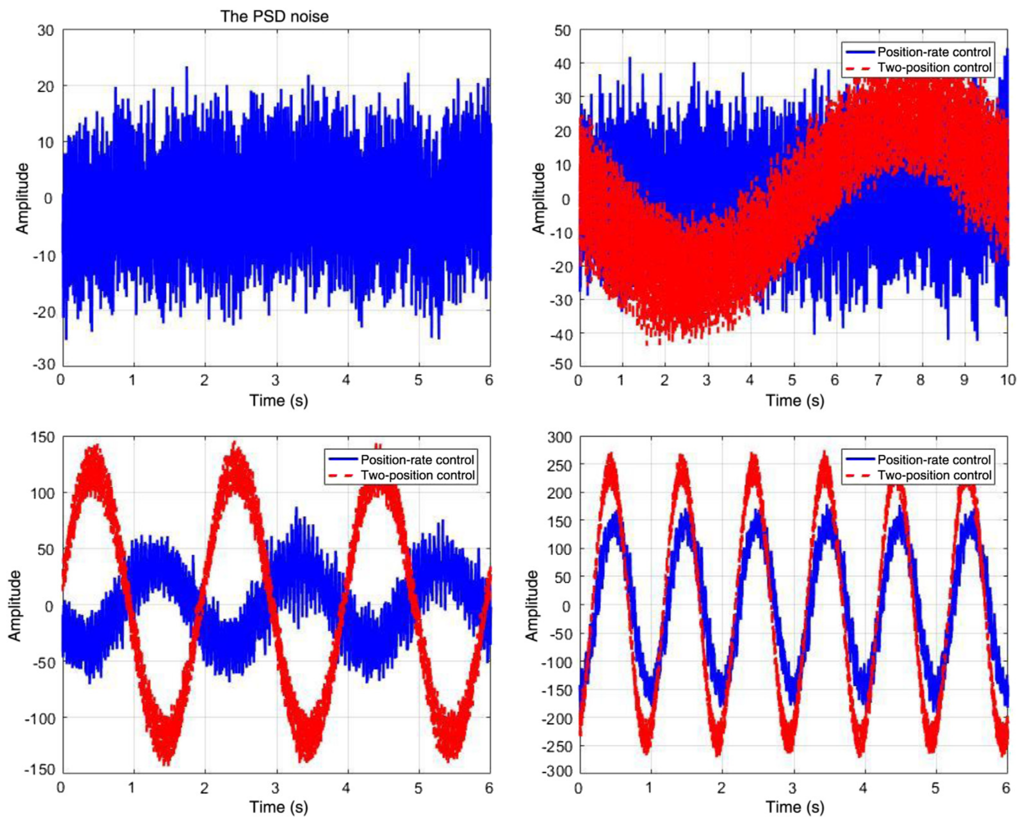

Fig. 9 Error comparisons between the position-rate control and the two-position control: (a) PSD noise, (b) error comparison at 0.1 Hz, (c) error comparison at 0.5 Hz, and (d) error comparison at 1 Hz.

Table 1 Error attenuation performance comparisons in low frequency.

Frequency (Hz)	With RFC (dB)	With PFC (dB)
0.1	−43.5	−37.5
0.5	−35.6	−26.0
1	−25.5	−21.4

4 Discussions

The rate feedback control effectively improves the error attenuation performance of the system. Given that the linear encoder has such good rate measurement performance, another control mode can be considered, which is the rate feedforward control mode. The control mode with feedforward control is shown in Fig. 10.

To protect the output of the system from disturbance, it is necessary to satisfy the following requirement:

$$C_f(s)V(s) + s = 0. \tag{12}$$

Therefore, the controller $C_f(s)$ needs to satisfy the following condition:

$$C_f(s) = -sV^{-1}(s). \tag{13}$$

Thus, using the linear encoder, a position sensor, to measure the disturbance and then implement the disturbance feedforward control should effectively improve the tracking accuracy of the system.

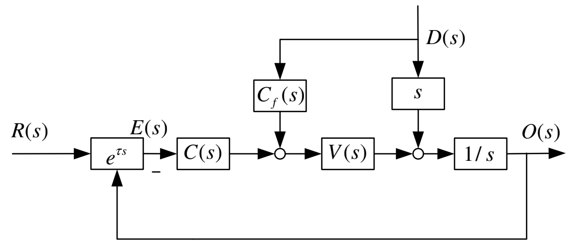

Fig. 10 Functional block diagrams with disturbance feedforward control.

5 Conclusions

The position-rate control mode is proposed to improve the tracking and pointing performance of the tip-tilt mirror system. Based on the practical application of linear encoder, the control modes of the tip-tilt mirror are discussed. The conditions of implementing rate feedback to the tip-tilt mirror system are given from two aspects of closed-loop stability and error attenuation. The experimental results show that the position-rate control method can effectively improve the bandwidth and trajectory tracking capability of the closed-loop system. This study did not consider the influence of external disturbance. In future work, the influence of external disturbance should be concentrated. Therefore, appropriate methods should be considered to suppress the disturbance and improve the tracking performance. Feedforward control is a good method, which will be our next work.

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