Analysis and demonstration of PID algorithm based on arranging the transient process for adaptive optics

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Received July 11, 2013; accepted September 25, 2013; posted online October 31, 2013

The fastness and robustness of a control algorithm are highly important in the performance of adaptive optics systems. The proportional-integral-derivative control with arranging the transient process, which is designed using a tracking differentiator, is applied into an adaptive optics system. This control algorithm greatly improves the dynamic properties of the control system. To identify the underlying reasons for these improvements, the influence of the control algorithm is theoretically discussed. The control algorithm is verified by a simple adaptive optics system for tip/tilt correction. The experimental results demonstrate that the control algorithm is fast and robust.

OCIS codes: 010.0010, 010.1080.

doi: 10.3788/COL201311.110101.

Adaptive optics is used to improve the performance of optical systems by real-time compensation for aberrations[1−3], such as atmospheric turbulence, optical fabrication errors, thermally induced distortion, or laser device aberrations. These aberrations reduce the peak intensity, smear an image, or decrease the laser intensity propagating to a target. Among the aberrations, the atmospheric turbulence rapidly varies in space and time. To correct the aberration induced by atmospheric turbulence, a fast and robust control algorithm is especially necessary. In astronomy, the resolution of ground-based large-aperture telescopes is greatly limited by atmospheric turbulence, which leads to severe distortions of the wavefront. Wavefront distortion may be solved using adaptive optics by compensating it in real time. Fedrigo *et al.*[4] improved tip/tilt control using Kalman filters and predictors to restrain noises and achieve high Strehl ratio. Roux. *et al.*[5] presented an optimal closed-loop control law with turbulence estimation and examined it by a simulated adaptive optics system. Frazier *et al.*[6] used H-infinity techniques to control the robustness of adaptive optics system. Baudouin *et al.*[7] applied H-infinity control of adaptive optics system to shorten the response time and strengthen the disturbance rejection.

In this letter, the algorithm of proportional-integral-derivative (PID) control with arranging the transient process (ATTP) is analyzed and applied in a simple adaptive optics system. The influence of ATTP on PID controllers is theoretically introduced. The approach to designing ATTP using a tracking differentiator is discussed. Considering tip/tilt correction as an example, the performance of the PID control with ATTP in a simple adaptive optics system is then investigated. The characteristics and advantages of the proposed control algorithm are examined.

In the control field, the dynamic properties of the control system are totally embodied in the transient process. ATTP is one of the most effective ways for improving the dynamic properties of a control system[8−12].

The setpoint sometimes varies in a step-like manner. Therefore, the output of a control system cannot track the setpoint immediately. To solve this problem, the setpoint (shown as solid line in Fig. 1), with ATTP, is replaced with successive intermediate setpoints called relay setpoints (shown as dotted line in Fig.1) during the transient process. With the series of relay setpoints, the steady state of the control system can be achieved rapidly, and the dynamic properties of the control system can be improved. In adaptive optics, shortening the time of the transient process of tip/tilt correction is a very effective technique to reduce the halo of a long-exposure image and increase its Strehl ratio. The influence of ATTP on controllers is discussed theoretically.

The discrete PID controller can be described as[13]

$$\begin{aligned} U(k) =& K_\mathrm{p} e(k) + K_\mathrm{i} \sum_{j=1}^{k} e(j) + K_\mathrm{d}[e(k) - e(k-1)] \\ =& U_\mathrm{p}(k) + U_\mathrm{i}(k) + U_\mathrm{d}(k), \end{aligned} \quad (1)$$

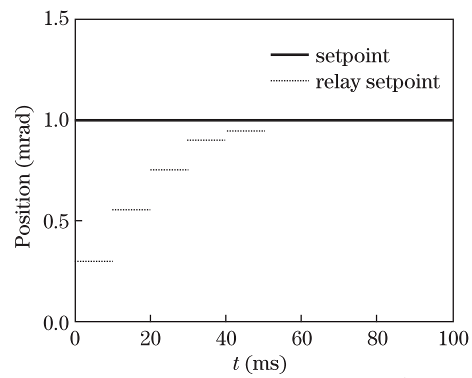

Fig. 1. Setpoints with and without ATTP.

where $U(k)$ is the output of the PID controller at the time k, e is the error, K_p, K_i, and K_d stand for the proportional, integral, and derivative coefficients, respectively, and $U_\mathrm{p}(k)$, $U_\mathrm{i}(k)$, and $U_\mathrm{d}(k)$ are the outputs of the proportional, integral, and derivative controllers at the time k, respectively.

The output of the proportional controller without ATTP would always be positive or negative until the output of the control system achieved the setpoint. Its adjustment in the single direction results in overshooting more easily compared with the proportional controller with ATTP, the output of which may be positive or negative. Hence, the dynamic properties of the control system would be improved with ATTP.

The output of the integral controller without ATTP saturates easily because of the larger error. Integral separation is usually used to solve this problem. However, considering that a threshold is always needed, the integral controller is only effective when the output of the control system is close to the setpoint. Given that the error of the integral controller with ATTP is much smaller than that of the controller without ATTP, it is more effective for the whole transient process. The integral controller with ATTP can also achieve a smooth transient process.

The derivative controller without ATTP curbs the change in the output of the control system. On the contrary, the derivative controller with ATTP not only restrains the output of the control system but also stimulates it to approach the relay setpoint[10].

Aforementioned characteristics and processes demonstrate that the dynamic properties of a PID controller can be improved with ATTP. Hence, the transient process should be designed properly.

A tracking differentiator, which generates the derivative signal by the difference of two inertial processes, can greatly restrain the noises of the derivative signal. The transient time of the control system can also be shortened using the derivative signal. In this letter, a tracking differentiator is adopted to arrange the transient process. The discrete form of the tracking differentiator can be expressed as[14]

$$\begin{cases} x_1(k+1) = x_1(k) + hx_2(k), \\ x_2(k+1) = x_2(k) + hF[x_1(k) - x(k), x_2(k), r, h], \end{cases} \tag{2}$$

where h is the filtering factor, r is the velocity factor, $x(k)$, $x_1(k)$, and $x_2(k)$ are the input, tracking, and tracking derivative signals at the time k, respectively. F is the optimal control synthesis function, which is described as

$$\begin{cases} d = rh, \quad d_0 = hd, \quad y = x_1 + hx_2 \\ a_0 = \sqrt{d^2 + 8r\,|y|} \\ a = \begin{cases} x_2 + \dfrac{a_0 - d}{2}\mathrm{sign}(y), & |y| > d_0 \\ x_2 + \dfrac{y}{h}, & |y| \leqslant d_0 \end{cases} \\ F(x_1, x_2, r, h) = \begin{cases} -r\mathrm{sign}(a), & |a| > d \\ -ra/d, & |a| \leqslant d \end{cases} \end{cases} . \tag{3}$$

To examine the characteristics of the PID control algorithm with ATTP and show the advantages of the control algorithm used in adaptive optics, a series of experiments are designed and implemented. Considering tip/tilt correction as an example, the experimental setup is shown in Fig. 2. The first fast-steering mirror (FSM1) is used to simulate the tip/tilt turbulence of the atmosphere. The quadrant photodetector (QPD) is used as wavefront sensor to measure the tip/tilt generated by the FSM1. The obtained tip/tilt information is sent to the controller through an analog–digital converter (ADC). The control signal generated by the controller with ATTP using a tracking differentiator is utilized to control the second fast-steering mirror (FSM2) through a digital–analog converter (DAC). The QPD and the FSM2 communicate with the controller by the sampling card. The sampling period is set to 5 ms. The precise control of the FSM2 can correct the tip/tilt generated by the FSM1 to improve the image obtained in the long-exposure mode on the charge-coupled device (CCD) imaging camera.

The QPD is the key component in the sensing of the tip/tilt in the above adaptive optics system. The QPD has four separate photoactive sections (I, II, III, and IV), as shown in Fig. 3. The optical signal incident on the QPD is separated into areas A, B, C, and D, and these photoactive sections generate corresponding voltages V_A, V_B, V_C, and V_D. Each voltage is proportional to the light power incident on the corresponding area. The deviation of the centroid of the light spot incident on the QPD from the center of the detector can be expressed as $x$diff and $y$diff in the x and y directions, respectively, as

$$\begin{cases} x\mathrm{diff} = \dfrac{(V_\mathrm{A} + V_\mathrm{C}) - (V_\mathrm{B} + V_\mathrm{D})}{V_\mathrm{A} + V_\mathrm{B} + V_\mathrm{C} + V_\mathrm{D}} \\ y\mathrm{diff} = \dfrac{(V_\mathrm{A} + V_\mathrm{B}) - (V_\mathrm{C} + V_\mathrm{D})}{V_\mathrm{A} + V_\mathrm{B} + V_\mathrm{C} + V_\mathrm{D}} \end{cases} . \tag{4}$$

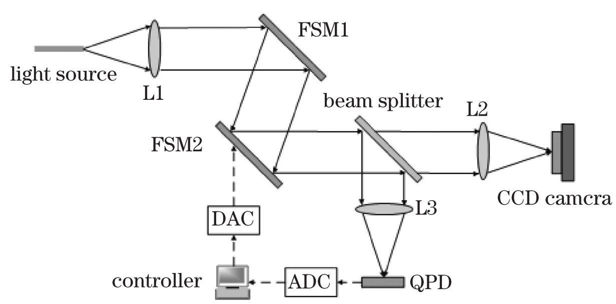

Fig. 2. Schematic of the experimental setup with L1, L2, and L3 lenses.

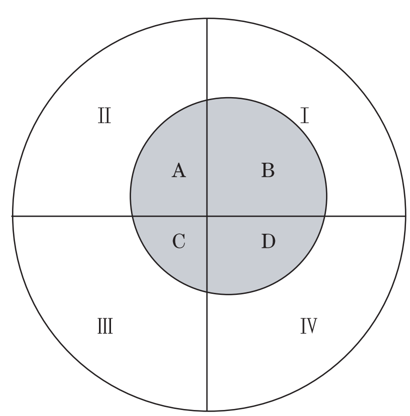

Fig. 3. Schematic of the QPD.

$x$diff and $y$diff are not equal to zero until the tip/tilt is zero in the corresponding direction. In this case, the image will not move. The sharpness of the image for a prolonged exposure can be improved greatly. Hence, $x$diff and $y$diff can be considered as merit functions to determine whether the tip/tilt has been corrected. Given that the x and y directions have similar behavior, the x direction is used as an example to verify our control algorithm, which is examined through the dynamic properties of the control system stimulated by the step signal.

The experimental results with and without ATTP are shown in Fig. 4. The parameters of the PID controller are tuned using the method of the critical proportional band. As shown in Fig. 4, the transient time is approximately 60 ms for the PID controller without ATTP (shown as the dash curve). Oscillations are generated for tuning the control parameters with larger values (shown as dash-dot curve). The transient time for the controller with ATTP decreased to 35 ms (shown as solid curve), which is much shorter than that without ATTP. The control algorithm with ATTP is evidently markedly superior to that without ATTP. In adaptive optics, a faster transient process indicates better long-exposure image quality. Accordingly, the controller with ATTP is much more suitable for adaptive optics.

The experimental results using different control parameters with ATTP are illustrated in Fig. 5. The same step signal is used for different conditions to test the robustness of the control algorithm. Although the control parameters differ, the experimental curves are similar. Hence, the PID controller with ATTP is robust, and the robustness of the controller decreases the difficulty of the parameter tuning. The robustness of the control algorithm can ensure the efficiency of adaptive optics system in most cases.

The experimental results clearly show the advantages of the control algorithm. The control algorithm is applied to adaptive optics system for tip/tilt correction. Tip/tilt is introduced randomly in the system using the FSM1 at a frequency of 10 Hz. The FSM2 is used to correct the tip/tilt at a frequency of 200 Hz. To obtain a higher Strehl ratio image for a long exposure time, the transient process is arranged to achieve a good correction of tip/tilt. The image energy distribution of three dimensions with and without tip/tilt corrections (the exposure time of the CCD-imaging camera is set to 30 s) is shown in Fig. 6. The gray value increased from 65 to 104

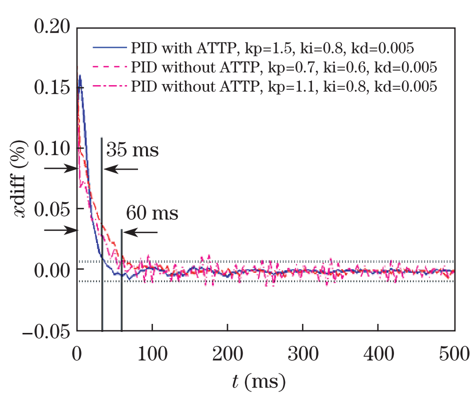

Fig. 4. Output signal of the QPD with and without ATTP.

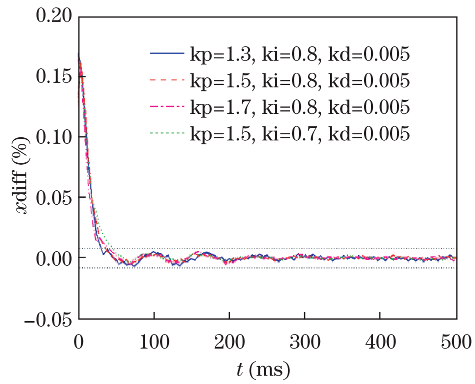

Fig. 5. Output signal of QPD using different control parameters with ATTP.

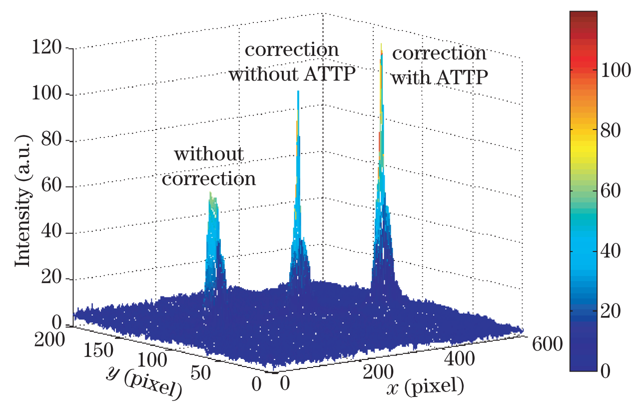

Fig. 6. Image energy distributions of three dimensions with and without corrections.

after the correction without ATTP and from 65 to 119 after the correction with ATTP. Obviously, the energy is more concentrated after the correction with ATTP. The image shows that the performance of the optics system improved greatly after the tip/tilt correction with ATTP.

A PID control algorithm with ATTP has been verified using a simple adaptive optics system. The experimental results show that the proposed control algorithm is highly robust and fast. With ATTP, the dynamic properties of PID controller have been greatly improved, which demonstrates that the proposed control algorithm is highly suitable for the correction of tip/tilt in adaptive optics. Furthermore, this algorithm is generic and can be extended to the correction of high-order aberrations in our future work. Although the correction of high-order aberrations with ATTP increases the complexity of the control algorithm and the economic burden of hardware, the application of ATTP can improve the dynamic property of the control system. Moreover, a high-performance adaptive optics system can be achieved.

This work was supported by the Dedicated Operation Funding for Astronomical Observation Stations and Facilities from the Chinese Academy of Sciences (CAS), the National Natural Science Foundation of China (No. 11203052), and the Special Funding for Young Researcher of Nanjing Institute of Astronomical Optics & Technology, CAS. We thank Dr. Kai Zhang of Nanjing Institute of Astronomical Optics & Technology.

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