Closed-loop control with a coupling factor using an AO system

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Abstract. To stabilize a closed-loop control for a wavefront correction of a distorted laser beam, the instrumentation of an adaptive optics system and the closed-loop wavefront correction algorithms were investigated. We proposed a new control algorithm using a coupling factor from the zonal and the modal ideas. Compensating for an arbitrary wavefront distortion of a laser beam in the real-time, the wavefront correction speed was 5 Hz using the proposed methods of a zonal control with a coupling factor. Although the correction speed is slower in the new algorithm, the correction accuracy is more stable. The experimental results show that the proposed algorithm is appropriate for the wavefront correction of a low frequency fluctuation.

1. Introduction

Adaptive optics (AO) system, which controls a wavefront in the real-time, is a technique widely used to enhance the performance of optical systems by compensating for a laser beam distortion through the atmosphere [1, 2]. For a high-power laser delivery system, we have developed a closed-loop AO system, which consists of a Shack-Hartmann wavefront sensor (SHWFS), a 37-channel deformable mirror (DM) and driver, and a main control computer. A personal computer is used to evaluate the wavefront sensor measurements and translate the signals into the control signals to drive the actuators of the DM. The speed and accuracy of this computation directly affect the closed-loop bandwidth of the system [3].

In this paper, the closed-loop wavefront correction was performed using the direct control algorithms developed by an AO system. The AO system controls the activation voltage of the actuators using the slope influence function of the DM. We found the relationship between the sub-apertures of the SHWFS and the 37 actuators of the DM. The zonal control technique was implemented using the slope influence function of the DM surface. In addition, we proposed new control algorithms with a coupling factor from the zonal and the modal control ideas. The new slope influence matrices from the coupling factor that constitute the combined zonal and modal estimation algorithms, lead to the slope influence function and the derivatives of the Zernike modes, respectively.

2. System instrumentation

The closed-loop control diagram of an AO system for a wavefront correction is shown in figure 1. The wavefront of the incoming laser beam is measured using the SHWFS that reflects from the DM. In our
designed AO system, the main control computer captured the wavefront spot images using a 12×12 array lens of the SHWFS to measure the local gradient of the wavefront. After calculating the wavefront distortions and the tip/tilt errors, the computer calculates the electrical voltages to compensate for the wavefront distortions using the DM. The closed-loop control of an AO system needs a proper algorithm, which is derived from the relationship between the SHWFS and the DM. Generally, the actuators’ position of the DM does not fit the subaperture of the SHWFS. Therefore, the SHWFS must measure the activation property for each channel of the DM. If the actuator of the DM is activated, it is influenced linearly by the surrounding actuators. The main control computer transmits the fixed voltage to each actuator of the DM and measures the shape of the mirror surface using the SHWFS. In this research, the zonal control algorithm was examined by driving the DM using the slope of the wavefront that was measured by the SHWFS in a direct way to compensate for the distorted wavefront composed of the wavefront reconstruction from the slope information [4, 5].

Figure 1. The schematic diagram of the closed-loop adaptive optics system for a wavefront correction.

We designed a robust main control computer system using an IBM compatible personal computer on the Windows operating system [6]. After the initialization of the AO system, the computer grabs a wavefront spot image and calculates a threshold value of the background noise. Data communication is synchronized between the main computer and the DM driver by receiving the same clock pulse from a pulse generator. The computer sends the control data to the DM driver through the differential driver. The differential driver converts the common grounded control voltages into differential control signals that are more robust than the noise signals [7, 8].

3. Results
The closed-loop wavefront correction is performed with the reference wavefront, which is the state of the estimated flat biased voltage. After applying the flat biased voltage, the adaptive optic system has some wavefront error because of the exposed air turbulence in the laboratory environment. According to the variation of time, the reference wavefront is measured in the real time by the SHWFS. A measured value is a pixel unit that measures the displacement of the Hartmann spots images stored from the CCD camera sensor to the image capturing board about the x-axis and y-axis. The average displacement of the reference wavefront spot images that were measured for more than an hour was 0.08 pixels, and the wavefront error range was 0.1-0.2 pixels. Also, the standard deviation was 0.02-0.04 pixels. From this result, the wavefront error was thought to be due to the edge effect of the whole aperture, but these values showed the same result at the edge as well as in the center of the wavefront.
Therefore, the measured value could analyze the basis error of this system. From the sensitivity of the SHWFS, the wavefront error of 0.2 pixels may be omitted because it is a small value of 0.018 waves.

![Figure 2](image)

**Figure 2.** The wavefront correction results of the direct zonal control and modal control for some wavefronts with aberrations. (a) Reference wavefront (0.05 waves) (b) distorted wavefront (2.088 waves) (c) First correction for the direct zonal control (0.34 waves: 83%) (d) First correction for the modal control (0.42 waves: 79%)

Figures 2 (a) and (b) show the reference and the distorted wavefronts measured by the SHWFS respectively. The wavefront correction experiments are performed using the direct zonal and the modal control algorithms. Peak to valley (PV) value of the wavefront measured after the first correction in each case is shown in figures 2 (c) and (d) respectively. The wavefront measured by the direct zonal and the modal controls becomes 0.38 waves and 0.42 waves, respectively. In the direct zonal control, the PV value of the wavefront in the second correction and the third correction were 0.19 waves and 0.15 waves, respectively. In the continually correcting case, the average value was 0.2 waves, and the correction ability was about 95%. However, there is a shortcoming in that the wavefront distortion by an atmospheric turbulence appears to be great. Beside the error sources of the previously analyzed algorithm, the nonlinearity and hysteresis of the actuators, an inaccuracy in measuring the coupling and the slope response are the main sources of error. Because of the limited fitting capability of the 37-channel wavefront sensing and correcting device, the local wavefront errors of a certain scale cannot be corrected. In the modal control, the speed of the main control system became slow, and the correction ability was lower than the direct zonal control. However, the modal controls have an advantage in that we can obtain wavefront aberration information.

The correction of the arbitrary wavefront was then performed with this system as shown in figure 3. The phase values of the reference and distorted wavefront were 0.017 waves and 3.05 waves, respectively. The phase value decreased rapidly under the control of the zonal closed-loop, but the phase values of the zonal control with a coupling factor decreased slowly and were better than those of the zonal control. The minimum phase values of the zonal and the proposed zonal correction were 0.14 waves and 0.09 waves, respectively. Although the correction speed became slow in the proposed algorithm, the correction accuracy was more stable. We found that the proposed algorithm was appropriate for the laser wavefront correction of a low frequency fluctuation.
4. Conclusions
We developed a closed-loop AO system and conducted a wavefront correction experiment. We discussed the influence function for the correct interests of the DM, which is an important device in an AO system. Moreover, the manufactured DM driver is connected to the main control computer. We constructed a slope influence function for the relationship between the wavefront measurements device and the wavefront correcting device. Also, we constructed the SHWFS. The closed-loop connection of this device was made possible using a personal computer. The properties of the DM, or the surface flatness, were measured by the SHWFS; it had a base error of less than 1/4 wave. The wavefront correction ability and its speed were 5 waves and 10 Hz by a direct zonal control algorithm with the developed AO system. If the main control computer included a modal control algorithm, it calculated the wavefront aberration. In this process, we combined the zonal and modal calculation ideas and looked for the coupling factor. We constructed a slope influence function for the proposed zonal control from a coupling factor and implemented the wavefront correction experiment. The initial correction speed of the proposed control algorithm could be slow about 5 Hz, but we obtained an excellent correction result for the stability of the system. It is stable especially because it has dull external noise. Although the correction speed is slower in this new algorithm, the correction accuracy is improved. In conclusion, we found that the proposed algorithm is appropriate for a laser wavefront correction of a low frequency fluctuation.

Figure 3. The closed-loop correction of the arbitrary wavefront.

References
[1] Tyson R K 1998 Principles of Adaptive Optics (New York: Academic Press)
[2] Hardy J W 1998 Adaptive Optics for Astronomical Telescopes (New York: Oxford University Press)
[3] Seo Y -S, Baik S -H, Park S -K and Kim C -J 2001 J. Korean Phys. Soc. 39 891
[4] Southwell W H 1980 J. Opt. Soc. Am. 70 998
[5] Li X, Wang C, Xian H, Wu X and Jiang W 1999 Proc. SPIE 3762 116
[6] Baik S -H, Park S -K, Kim C -J, Seo Y -S and Kang Y -J 2002 proc. SPIE 4926 251
[7] Park S -K, Baik S -H, Seo Y -S, Kim C -J and Ra S W 2003 J. Korean Phys. Soc. 42 743
[8] Park S -K, Baik S -H, Kim C -J and Ra S W 2002 Opt. Laser Technol. 34 687