Robust model matching for an adaptive optics system

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***Abstract*—**Atmospheric turbulence is major obstacle to achieve high-resolution imaging of object since telescopes were invented. Adaptive optics is a developing technology, which is commonly used in ground-based astronomical telescopes to remove the effects of atmospheric distortion and improve the performance of optics system. To achieve high-resolution imaging of targets in space, it is of key importance to reduce the effects of atmospheric turbulence by operating a deformable mirror. Various computer control approaches have been applied to overcome this problem. However, these approaches tend to yield high-order complex controllers. In this paper, we propose a simple and tunable low-order robust controller design for an adaptive optics system based on the robust model matching method. The resultant robust compensator can be attached to any kind of existing AO control systems and the robustness can be tuned easily. Simulation and experimental results are presented demonstrating the efficiency of the proposed design.

***Keywords*—**Adaptive optics, control system design, modeling and identification, robust control.

I. Introduction

THE earth's atmosphere introduces aberrations to the wavefront from an astronomical object that is observed by a telescope on the earth's surface. The objective of an adaptive optics (AO) system [1], [2] in astronomy is to reduce, as much as possible, the effects of these aberrations in real-time by adjusting the shape of a deformable mirror (DM) to remove the aberration using closed loop feedback control.

Many feedback systems for AO systems have used classical integral feedback to measure and to reduce the wavefront error. In Japan, Hida observatory has an AO system as one of the observational equipments for solar observation. This AO system also uses integrator and is fully controlled with software in standard personal computers [3].

Although classical integral feedback of the measured wavefront works well provided in slow operating condition, increasing demand of the control performance, more sophisticated model-based control strategy is needed, and a practical AO system should be optimized to achieve its best possible performance. Advanced control theories such as neural networks [4], adaptive control [5], LQG [6], H-infinity [7], H_2 [8] and minimum variance control [9] have been applied to design AO systems and these results offer high performance.

However, these approaches tend to yield high-order complex controllers, and the real-time computational burden is a significant obstacle for realization of these potential performances. Moreover, because the AO systems are sensitive to variations in atmospheric turbulence, the non-stationary characteristic of atmospheric turbulence often brings to recalculate the control algorithms, or modify the control methods for the different atmospheric conditions and then the system must be re-optimized.

Reduced order tunable robust control is a promising solution to overcome the dilemma. There have been many studies about robust control system design. Among them, parallel-model-and-plant paradigm, referred to as Robust Model Matching (RMM) [10]-[12] is a natural and tractable approach to design and analysis of robust control systems.

In this paper, we have designed a robust compensator based on the RMM strategy. Our approach presents some major advances over previous controller design for an AO system. Firstly, design procedure is simple and yields low-order controllers. Secondly, robustness can be tuned easily. Thirdly, the robust compensator can be attached to any kind of existing systems.

The rest of the paper is organized as follows. In Section 2, we describe the experimental AO system that is set up a simulated atmosphere-telescope system in the laboratory. In Section 3, we explain about the plant modeling and identification. In Section 4, we remind the RMM and explain actual controller design for the plant. In Section 5, we made the performance evaluation of the designed robust compensator. Section 6 described the experimental procedure of the system and analyzed the experimental results. Finally, concluding remarks are given in Section 7.

II. AO system description

Generally, an AO system consists of three main parts: a sensor referred to as the wavefront sensor (WFS), a compensator referred to as the control computer (CC), and a compensating device referred to as the deformable mirror (DM).

Manuscript received xxx revised xxx.

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The WFS determines the phase of an optical wavefront and is typically made up of a charge-coupled device (CCD) camera and specialized software that calculates the wavefront estimates. The CC calculates the corrections to be made and is the heart of the system. Finally, the deformable mirror implements the corrections.

Our AO system is designed to compensate for low–frequency turbulence in rather short wavelength. It is equipped to the domeless solar telescope at the Hida observatory in Japan and modified for solar observations [13]. Fig. 1 illustrates the AO system hardware structure. There are three units for wavefront compensation, tip-tilt compensation and observation, and each of them is controlled by the respective PCs. All the PCs are connected with the LAN and controlled with a host PC.

Deformable mirror (DM) and the tip-tilt mirror are connected with each of their compensation PCs and the PCs calculate the detection result from a charge-coupled device (CCD) camera, and then, voltage is applied to the corresponding mirror and makes the mirror deformed. The tip-tilt mirror is used for the cancellation of the overall image-shift, while the DM corrects the wavefront disturbed by atmospheric turbulence to form a residual wavefront.

The AO system involves both discrete-time and continuous-time signals. The incident light is reflected from the DM to form a residual wavefront. If the AO system performed perfectly, the residual wavefront would be flat. The feedback measurement signal is formed by measure an approximation to the gradient of this residual use a wavefront sensor. The WFS forms its output by integrating residual wavefront within exposure, sampling at the end of integration. The outputs of the AO controller are discrete-time voltage commands. These are converted into continuous-time voltages to be applied to the DM by a zero-order hold (ZOH). Thus the measurement and control signals are inherently discrete-time, while the residual wavefront (which represents the performance of the AO system) is a continuous-time signal.

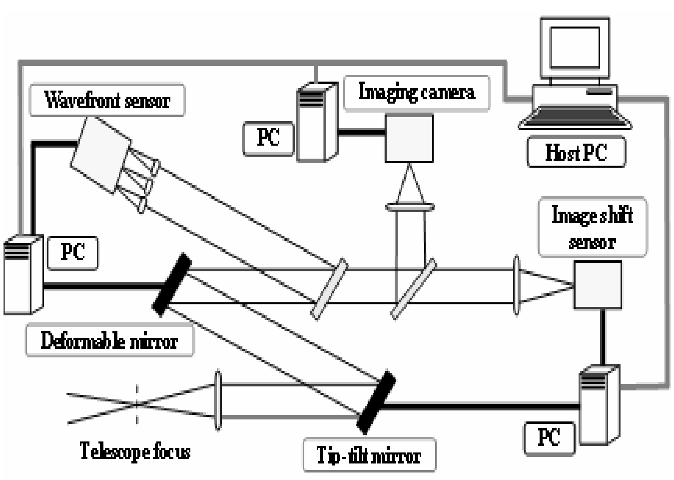


Fig. 1 Hardware structure of the AO system

The closed-loop block diagram of the AO system can be described as shown in Fig. 2. The DA is the digital-to-analog converter. The WFS digitizes the detector signals, and applies specific algorithms to derive the wavefront measurements. The HVA is the high voltage amplifier, it amplify the low voltage outputs of the DA to drive the actuators of the DM.

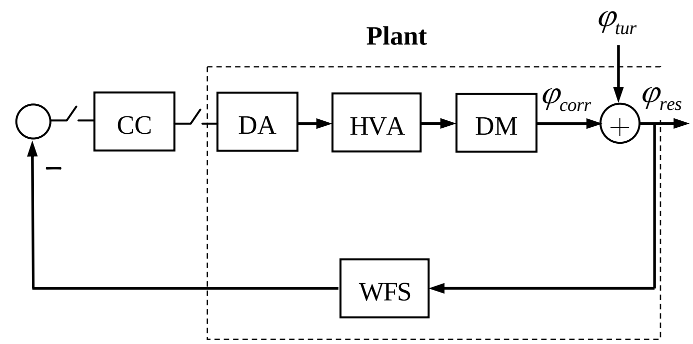


Fig. 2 Block diagram of the AO system

As shown in the Fig. 2, the input of the system is the uncompensated wavefront (atmospheric turbulence) whose value at a 2D (horizontal and vertical) point (x, y) and a time t is denoted by the $\varphi_{tur}(x, y, t)$. The correction introduced by the DM is denoted by the $\varphi_{corr}(x, y, t)$. The residual phase after correction: $\varphi_{res}(x, y, t)$ described as the following.

$$\varphi_{res}(x, y, t) = \varphi_{tur}(x, y, t) + \varphi_{corr}(x, y, t) \tag{1}$$

The principle of the AO control system is to eliminate the effects of the disturbance $\varphi_{tur}(x, y, t)$, thus making the residual wavefront $\varphi_{res}(x, y, t)$ as small as possible. The AO system uses the WFS measured (ideally flat) residual wavefront $\varphi_{res}(x, y, t)$ to estimate the aberration induced by the turbulence, and to adjust the shape of the DM.

III. Plant Modeling and Identification

The plant model of the AO system is theoretically derived as (2) in the reference [14].

$$G(s) = \frac{e^{-T_d s}(1 - e^{-Ts})^2}{T^2 s^2} \tag{2}$$

Here, T_d denotes computing time and T denotes integration time of the WFS.

Instead above theoretical model, we have conducted several laboratory experiments and deduce practical model of our actual AO system to design robust controllers. We added stepwise input to the plant and obtained the output signals, and estimated the plant model using System Identification Toolbox of MATLAB™. As a result, we consider that the transfer functions of both HVA and WFS in Fig. 2 can be approximated as unity. On the other hand, we assume that of DA and DM is approximated by a pure time delay and a second-order transfer function, respectively. Therefore, the plant can be expressed as the following transfer function.

$$G(s) = DM(s) \cdot DA(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \cdot e^{-T_d s} \qquad (3)$$

Finally the parameters are estimated as $\omega_n = 3098$, $\zeta = 0.626$ and $T_d = 0.001299$ whose fitness between the experimental output and estimated output is more than 98%. Fig. 3 shows the result window of the system identification toobox.

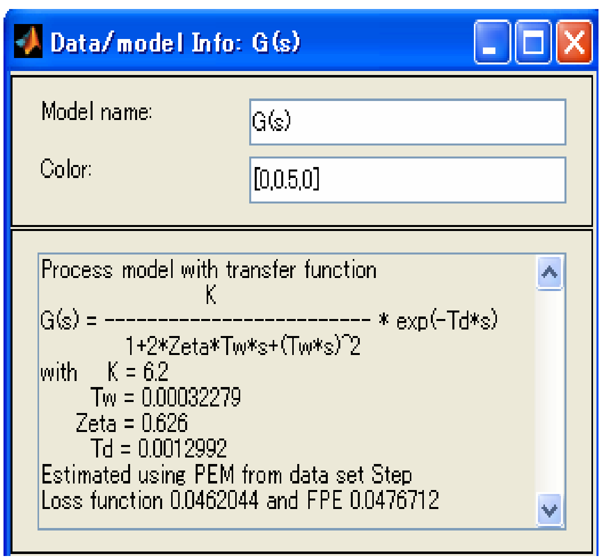


Fig. 3 System Identification result of the plant modeling structure

Fig. 4 shows step input responses of experimental and estimated plant.

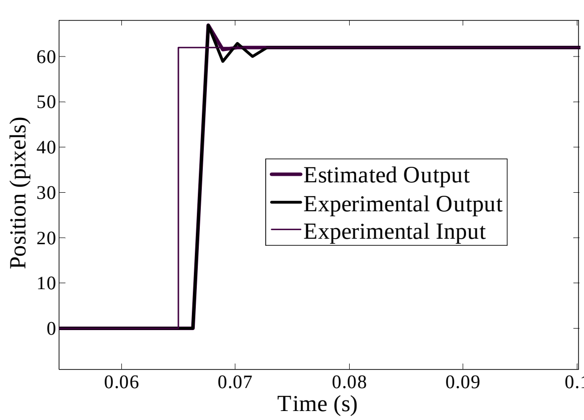


Fig. 4 Step input responses of real and estimated plant

IV. Robust Compensator Design

Robustness is an important subject for practical system designs based on model-based strategy. It is a significant property that allows the control system to maintain its function despite the environmental disturbances and the system uncertainties. Various designs have been developed from a variety of viewpoints that depend on plant uncertainties and control specifications [15].

In this section, robust model matching method is quickly summarized and then the proposed robust control AO system design based on the method is shown.

A Robust model matching

In [16] the relation between disturbances and model uncertainties was discussed, and the Base-Equivalent-Disturbances (BED) that represent both model uncertainties and real disturbances were defined in general control scheme. Design methods of attachable robust compensators for existing control systems were also proposed and referred to as RMM. The role of the attaching robust compensators is to attenuate the affect of BED on controlled outputs.

Regarding attachable compensators, both the performance and the configuration of the control system are important considerations. Parallel-model-and-plant structure is explicitly considered in several control strategies, such as Conditional Feedback [17], Passive Adaptive Control [18], Internal Model Control [19] and Disturbance-observer-based control [20]. In this framework, new controller architecture based on Youla parameterization in Two-degree-of-freedom scheme is discussed in [21]–[23] and a plug-in robust compensator [24] is proposed to exploit existing controllers.

Design procedures of above-mentioned compensators are simple and practical. However, they require corresponding transfer functions of existing control systems. Thus, they are only applicable to linear control systems, whose closed-loop transfer functions are obtainable.

Turning now to robust control design method, a practical approach to the design of attachable robust compensators has been developed for the LTI plant [25]. The principle behind this method is RMM, which make the input–output property of the augmented plant approaches to the nominal model, namely, the low sensitivity to external disturbance and modeling error. This objective is achieved by means of rejecting the equivalent disturbance that represents the modeling errors [26], [27]. Also, despite the parameters of the controlled plant changes greatly, a constant control performance can be obtained by setting the bandwidth.

The general architecture of RMM is illustrated as shown in Fig. 5, and the structure of the add-on compensator is illustrated in Fig. 6. Here, the notation used in this paper is as follows:

$r \in R^m$: reference inputs,

$u \in R^m$: control inputs,

$z \in R^m$: controlled outputs,

$y \in R^s$: measurable variables,

$v \in R^m, v^* \in R^s$:conceptual signals added to respectively, u and y ,

$q \in R^l$: disturbances.

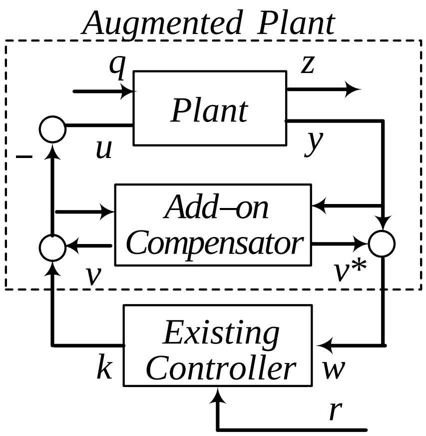


Fig. 5 General RMM configuration

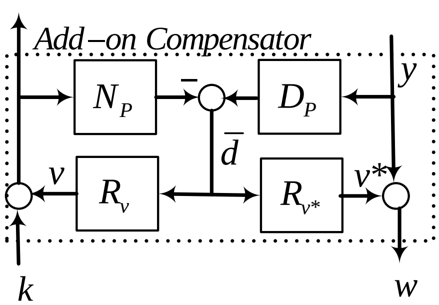


Fig. 6 Structure of the add-on compensator

The plant transfer function between u and y is expressed with normalized left coprime factorization as,

$$G(s) = D_P(s)^{-1} N_P(s) \,. \tag{4}$$

The $\bar{d}$ is base equivalent disturbances which represents any real disturbance and model uncertainties. The closed-loop transfer matrix from $\bar{d}$ to z : $W_{\bar{d}z}$ is written as,

$$W_{\bar{d}z} = {}_E W_{\bar{d}z} + {}_E W_{vz} \cdot R_v + {}_E W_{v^*z} \cdot R_{v^*} \,, \tag{5}$$

where, ${}_E W_{\bar{d}z}$, ${}_E W_{vz}$ and ${}_E W_{v^*z}$ denote transfer matrix of an existing control system (without add-on compensator) between $\bar{d}$ to z , v to z and v^* to , respectively.

The robust compensator design is minimizing the $W_{\bar{d}z}$ exploiting free parameters R_v and R_{v^*}.

The RMM has the following properties,

1. The add-on compensator can be attached to any existing control systems,
2. The add-on compensator improves robustness without changing feed-forward properties,
3. The add-on compensator is conditional controller and easy to tune.

B RMM applied to the AO system

In this subsection, we design a robust compensator for the AO system based on the RMM strategy.

If the plant is minimum-phase and the number of inputs is same as the number of outputs, the add-on compensator can be simplified as shown in Fig. 7. And also, the $W_{\bar{d}z}$ can be expressed simply as,

$$W_{\bar{d}z} = {}_E W_{\bar{d}z} (I - F) \tag{6}$$

Here, *F* is the row-pass filter which adjusts the robustness.

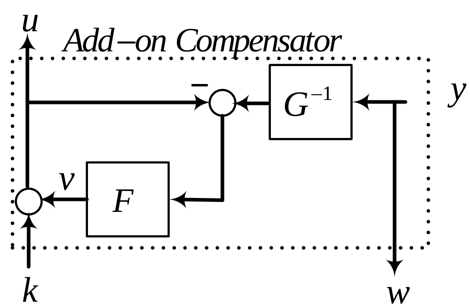


Fig. 7 Simple add-on compensator

The plant *G(s)*, derived by (3), however, includes the time delay that is not invertible. Thus, we introduce the Smith predictor [28] to the add-on compensator. A Smith Predictor is commonly used in feedback control of plants with time delays to assure nominal stability of the closed loop system. A criticism of the Smith predictor which is often made is that controllers with that structure can be very sensitive to modeling errors, particularly as regards misspecification of time delays in the plant. However, the performance of the Smith predictor can be easily improved by tuning the time delay as well as based on an accurate model of the plant.

The structure of robust compensator based on RMM combined with the smith predictor is then constructed as shown in Fig. 8.

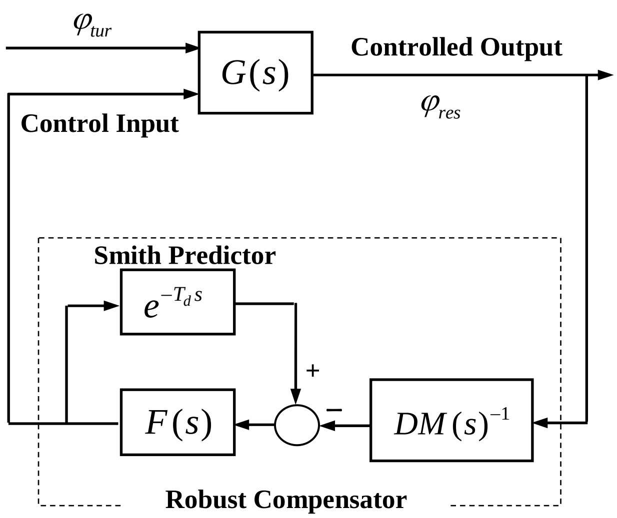


Fig. 8 Proposed robust AO control system.

The transfer function of the robust AO control system between φ_{tur} and φ_{res}: $W_{\varphi\varphi}$ is easily derived as,

$$W_{\varphi\varphi} = e^{-T_d s}(I - F)\,. \tag{7}$$

The $F(s)$ is a low pass filter that makes $DM(s)^{-1}$ proper and satisfies the low sensitivity as well as robust stability. Here, the low-pass filter is settled as,

$$F(s) = 1000/(s + 1000) \tag{8}$$

Based on the transfer function of the robust compensator, we obtained the control algorithms of the compensator by bilinear Z-transform that can be expressed in the following input: *y(k)* and output: *u(k)* differential equations:

$$\begin{aligned} u(k) &= 0.1042y(k) + 0.2756y(k-1) \\ &+0.02868y(k-2) - 0.005088y(k-3) \\ &+0.9624u(k-1) + 0.02646u(k-2) \\ &+0.011u(k-3) \end{aligned} \tag{9}$$

The proposed approach is more tractable because the design procedure is much simpler and generally solution has lower order than conventional approaches.

V. Robust performance evaluation

In this section, we evaluate the proposed AO system comparing with AO system with classical pure integral feedback.

First, we compare sensitivity of both systems which is one of the most important features of the system. Fig. 9 shows the gain diagram of transfer functions: $W_{\varphi\varphi}$ of both systems.

The cut-off frequency for the AO system with pure integrator is about 17 rad/sec (2.8Hz); on the other hand, that with the robust compensator is about 314 rad/sec (50Hz). For frequencies lower than this bandwidth, the system is able to attenuate the turbulence. From the Fig. 9 we can learn that the robust control system have better frequency domain comparing with the pure integrator system. More over, the bandwidth of the proposed AO system can be easily tuned by changing the bandwidth of the low-pass filter *F(s)*.

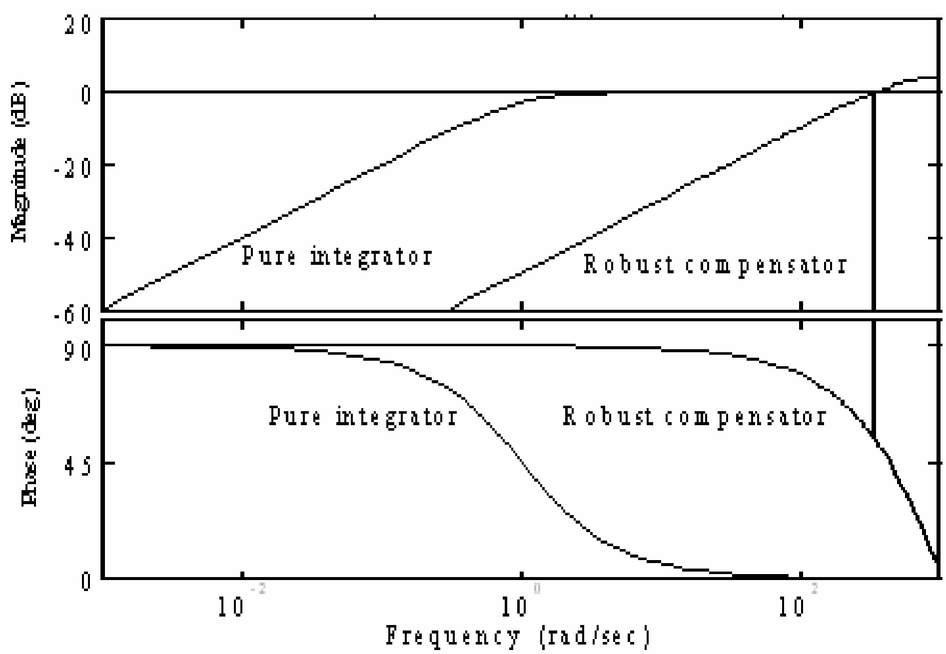
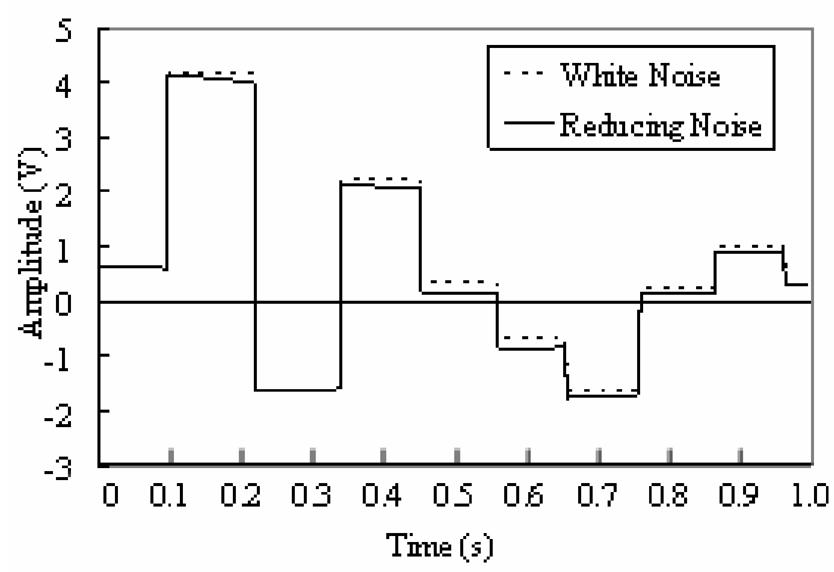
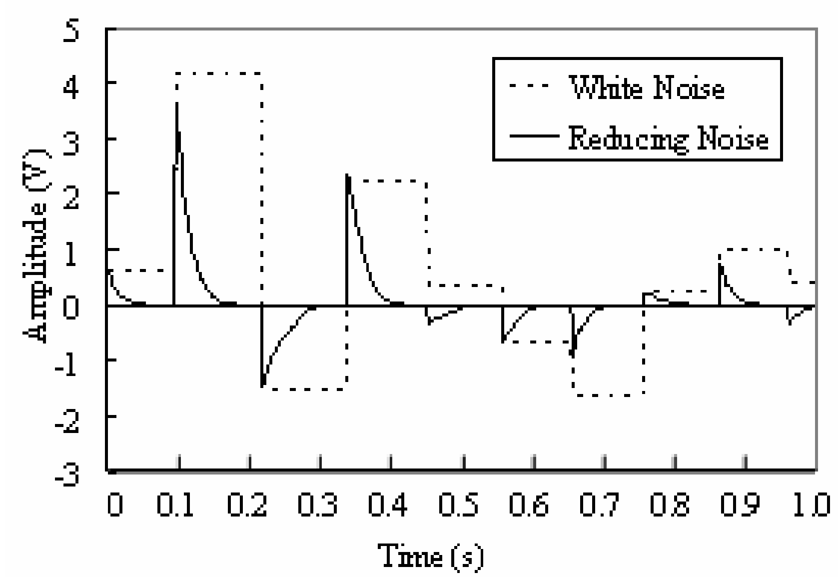


Fig. 9 Gain diagram of the AO systems

Moreover, in order to verify the robustness of the AO system, we introduced some noises and made simulation with MATLAB. As shown in Fig. 10, the Band-Limited white noise acted as uncompensated wavefront, Fig. 10(a) and Fig. 10(b) show the values of the residual phase after reducing the noise, by using pure integrator and robust compensator respectively.



(a) Using pure integrator



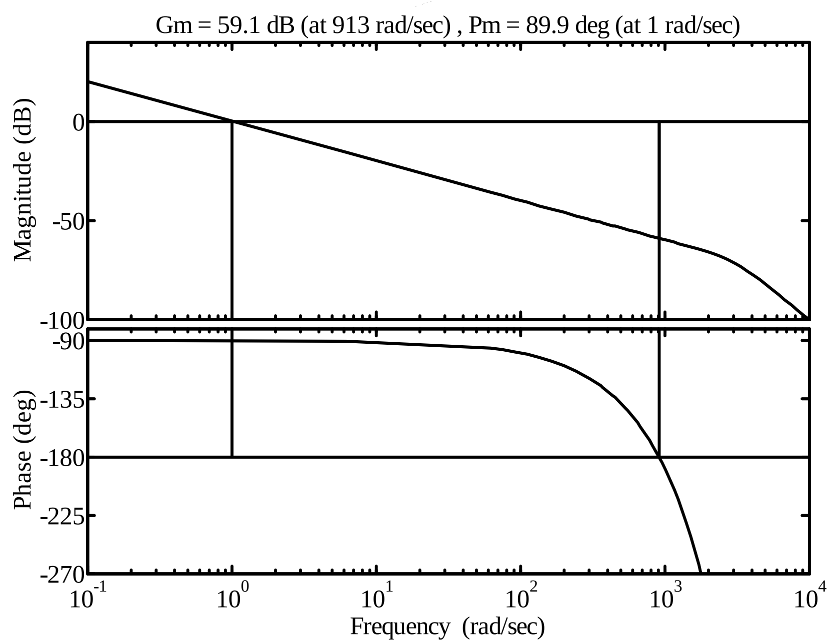
(b) Using robust compensator

Fig. 10 Simulation results of reducing the noise

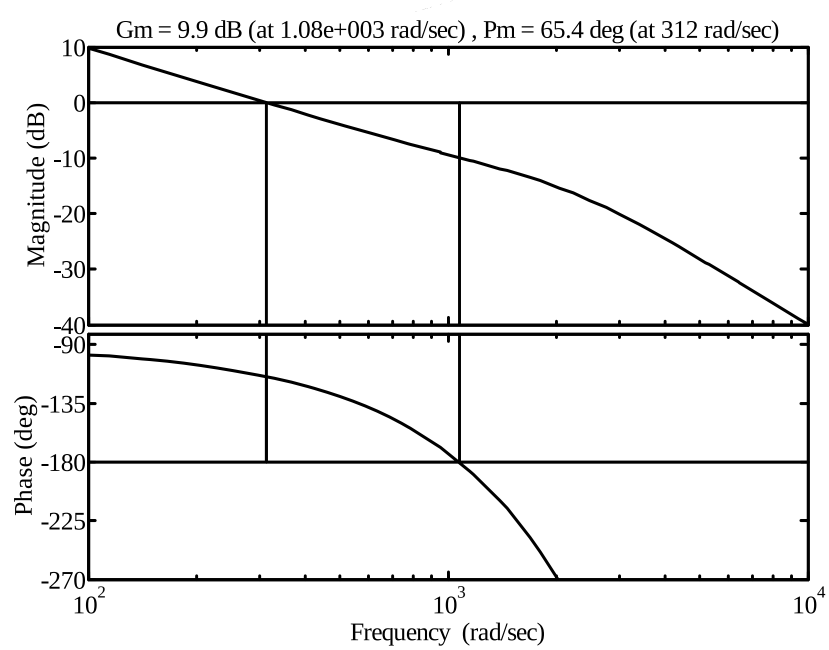
As shown in the Fig. 10, the value of the residual phase is tending to be minimized instantly by using robust compensator, comparing to the use of pure integrator, which means that the AO system with robust compensator has the better robustness than the system with pure integrator.

It is well known that robustness (disturbance attenuation) is incompatible with robust stability. We have checked the gain margin and phase margin of both control systems. Fig. 11 shows the frequency response characteristics of open-loop transfer functions of the AO system using pure integrator and robust compensator, respectively. For frequencies lower than this bandwidth, the AO system is able to apply a gain in the loop, for example, to compensate for perturbations. For higher frequencies, the AO system attenuates the signals in the loop: no more correction can be obtained. This bandwidth gives a first idea of the frequency domain where the AO system is efficient. It is useful to compare the intrinsic capability of different AO systems.

Comparing both characteristics, we see that the AO system with pure integrator have more margins, however, the AO system with robust compensator have also enough margins.



(a) System using pure integrator



(b) System using robust compensator

Fig. 11 Frequency response characteristics of the systems

I. LABORATORY EXPERIMENTATIONS

In order to investigate the practical performance of the AO system, the laboratory experiments were conducted. Fig. 12 shows the photograph of the optical setup of the experimental AO system.

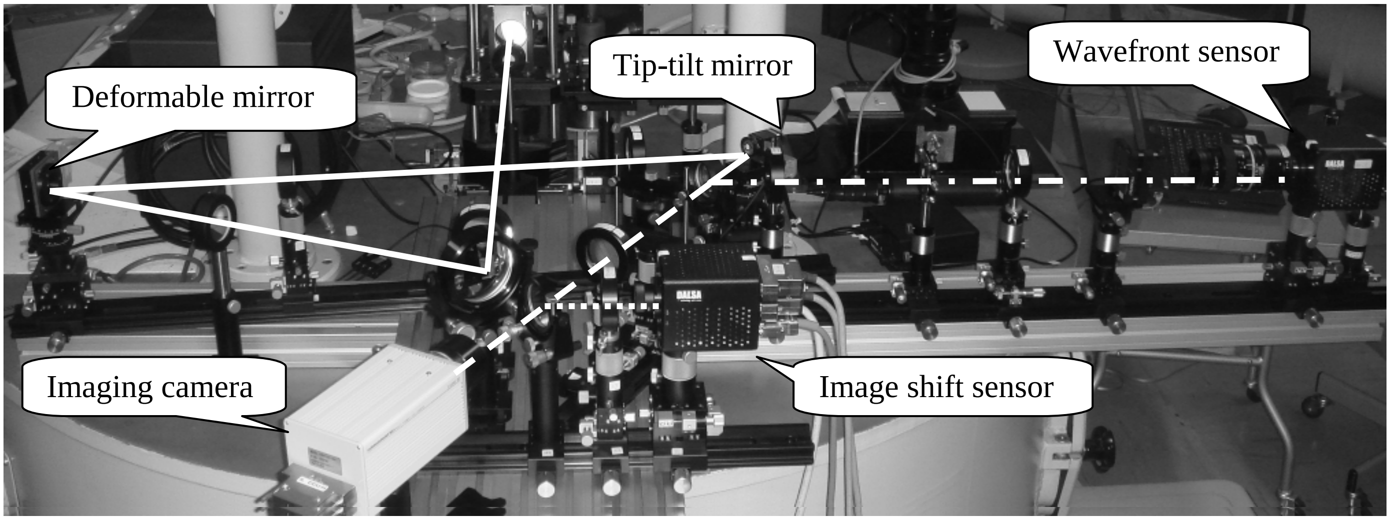


Fig. 12 Photograph of the optical setup of the AO system

The compensated light is finally led to the imaging camera. The image-shift sensor is just a high-speed CCD camera. Images taken with the camera are processed with a PC to obtain the image centroids. The image-shift vector is specified as the difference between the image centroid of a target frame and that of the first frame. From the image-shift vectors, voltages applied to the mirror are determined. The tip-tilt mirror is mounted on a piezo-driven tilting stage. The stage tilts horizontally and vertically according to voltages applied to two piezo-devices. We regarded the relation between the tilting amount and the applied voltage as linear and then experimentally measured the proportional coefficients. The wavefront sensor is composed of a microlens array and a high-speed CCD camera. The deformable mirror has nineteen piezo-actuators.

An imaging camera captures solar images after the compensation of wavefront degraded by atmospheric turbulence.

All the PCs in our system are connected by a network, and each process in every PC is controlled by a host PC. Its software system has a graphical user interface (GUI), which makes it easy for users to operate the AO system.

We set up a simulated atmosphere-telescope system in the laboratory where a deformable mirror, referred to as a turbulence mirror, causes turbulence on the wavefront from a H_e-N_e laser, a pinhole acts as an object and a lens functions as a primary mirror of the telescope. To simulate atmospheric turbulence, we introduced another deformable mirror that is a membrane type with 19 channels.

Table 1 lists the devices used in the system and their specifications.

We carried out the experiments by putting the AO module behind the simulated atmosphere-telescope system. There are two driving modes for the mirror: tip-tilt and turbulence. In the tip-tilt mode, the mirror surface remains flat but inclines with a given oscillation frequency. When the turbulence mode is selected, the mirror surface is corrugated with a given frequency. These frequencies can be tuned by a parameter in the software.

In our experiment, we set the oscillator frequency in the tip-tilt mode and changed the tip-tilt frequency. Table 2 listed the results of 32, 64 and 99Hz. From the table we can see that with applying the AO system, by the frequency of 32 and 64 Hz, the deviations both in horizontal and vertical directions were improved significantly using the robust compensator comparing to the use of pure integrator. However, as the driving frequency increased, the results are no more improved comparing to the use of pure integrator.

We consider that one of the main reasons is the insufficiency of the processing speed as the driving frequency increased, because the whole AO system is a software-oriented system. This kind of problems should be overcome by simplifying the processing procedure as well as by improving the processing speed of the AO system. Also, we are considering the way to adjust the parameters of the robust compensator, in order to apply more precise control algorithm.

Table 1 Devices and their specifications

Deformable mirror	Continuous facesheet, 19 piezo-actuators, hexagonal array, 30 mm diameter
Tip-tilt mirror	Two-axis mount, 2 piezo-actuators
Microlens array	25 subapertures, 5×5 orthogonal array, 19 mm focal length
Sensing cameras	256×256 pixels, $10\,\mu m$ pixel size, 955 maximum frame rate
Imaging camera	1280×1024 pixels, 9 or 18 Hz frame rate (1×1 or 2×2 binning)
Tip-tilt control	Standard PC with Pentium Ⅳ 280 Hz
Wavefront control	Standard PC with Pentium Ⅳ 300 Hz

Table 2 Deviations of centroid positions

Oscillation frequency (Hz)	Without AO		With AO (pure integrator)		With AO (robust compensator)	
	Horizontal (pixels)	Vertical (pixels)	Horizontal (pixels)	Vertical (pixels)	Horizontal (pixels)	Vertical (pixels)
32	3.519353	0.169163	3.521988	0.164648	1.713947	0.128598
64			3.515884	0.155137	3.283632	0.142491
99			3.496365	0.150535	4.352074	0.145023

Ⅶ. Conclusions

In this paper, we have designed a simple and practical robust compensator for an AO system, based on the RMM strategy combined with the Smith predictor. The robust compensator makes the input–output property of the augmented plant approaches to nominal plant model. This objective is achieved by means of rejecting the equivalent disturbance that represents the modeling errors. Also, despite the parameters of the controlled plant changes greatly, a constant control performance can be obtained by setting the bandwidth. Because this method of control which is based on an accurate model of the plant, we conducted several laboratory experiments to acquire precise plant model. Since the design procedure is simple and yields low-order controllers, there is less real-time computational burden than high-order complex controllers. Also, the robust compensator can be designed without information of the previously designed controller, and the compensator is constructed in a different way from previous controllers, the robust compensator can be attached to any kind of existing systems including nonlinear control scheme. In addition, because the compensator design is rather flexible, robustness can be tuned easily.

To investigate the robustness and the performance of the AO system, we made numerical simulations as well as laboratory experimentations. Simulation and experimental results shows that the system with the robust controller has improved significantly comparing to the classical integral feedback control system.

For the future work, the processing speed of the AO system should be improved in order to overcome the insufficiency of the processing speed..

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