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Adaptive Optics with Adaptive Filtering and Control*

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***Abstract*— This paper presents a quasi adaptive control method for adaptive optics. Adaptive compensation is needed in many adaptive optics applications because wind velocities and the strength of atmospheric turbulence can change rapidly, rendering any fixed-gain reconstruction algorithm far from optimal. The performance of the new method is illustrated by application to recently developed simulations of high energy laser propagation through extended turbulence.**

I. Introduction

Adaptive optics (AO) refers to the use of deformable mirrors driven by active control loops that feedback wavefront sensor (WFS) measurements to compensate for turbulence-induced phase distortion of optical waves propagating through the atmosphere [1], [2], [3], [4], [5]. These control loops reconstruct (i.e., estimate and predict) the phase profile, or wavefront, from the WFS data. The control loops in classical AO systems are linear and time-invariant (LTI), having fixed gains based on assumed statistics of atmospheric turbulence. Such control loops are not themselves adaptive, in the sense in which the term *adaptive* is used in the control and filtering community.

Adaptive compensation is needed in many AO applications because wind velocities and the strength of atmospheric turbulence can change rapidly, rendering any fixed-gain reconstruction algorithm far from optimal. Recently, adaptive wavefront reconstruction algorithms based on recursive least-squares (RLS) estimation of optimal reconstructor matrices have been proposed [6], [7], [8], [9]. In this approach, an adaptive control loop augments a classical AO feedback loop. Results in [7], [8], [9] have shown that the type of adaptive loops used here are robust with respect to modeling errors and sensor noise.

The real-time computational burden is a significant obstacle for adaptive wavefront reconstruction because the number of actuators and the number of sensors each can be on the order of 100 to 1000, while the digital control loops need to run at sample-and-hold rates of 1000 Hz and higher. It is a serious challenge to develop real-time adaptive algorithms with RLS parameter estimation for a problem with so many input and output channels. For the adaptive control loops proposed in [7], [8], a multichannel RLS lattice filter first presented in [10] has been reparameterized and embedded in an algorithm developed specifically for adaptive feedforward disturbance rejection in adaptive optics problems. This multichannel lattice filter preserves the efficiency and numerical stability of simpler lattices, while accommodating very large numbers of channels through a channel-orthogonalization process. Although the problem formulation and much of the structure of the adaptive control loops presented in [7], [8] and this paper do not require that a lattice filter be used for adaptive estimation of an optimal wavefront reconstructor, multichannel lattice filters do appear to be among the few classes of algorithms that can yield the speed and numerical stability required for real-time adaptive optics.

This paper presents three advances over previous publications on the use of adaptive filtering and control in adaptive optics. First, the adaptive loop is designed to use the closed-loop wavefront sensor vector as the input to the adaptive loop, as opposed to an estimate of the open-loop wavefront sensor vector used in previous publications on this subject. Second, extensive simulations for varied scenarios have shown that the quasi adaptive loop, which updates gains periodically from short data sequences, is essentially as effective as the fully adaptive loop, which updates gains at every time step. Finally, the adaptive optics simulations presented here are much more realistic than those in [7], [8], [11] because a recently developed adaptive optics simulation with high-fidelity wavefront propagation model and detailed sensor characteristics, including nonlinearities, is used. Furthermore, the application is more challenging than those in [7], [8] because the turbulence path is much longer.

II. Adaptive Optics Formulated as a Control Problem

Figure 1 shows a schematic diagram for generic adaptive optics problem in directed energy weapons. Actuators are distributed in a two-dimensional array over a deformable mirror. These actuators are driven to adjust the profile of the mirror surface and cancel the phase distortions induced in a beam of light as it propagates through atmospheric turbulence. A wave front sensor (WFS) is used to measure the residual phase profile, using an array of subapertures that sense the spatial derivatives, or slopes, of the profile on a grid interlaced with the locations of the actuators. The purpose of AO system is to compensate the outgoing high energy laser for the wavefront error that will be induced by atmospheric turbulence, so that the laser forms a tight spot (image) on the target. The control system uses a beacon created by

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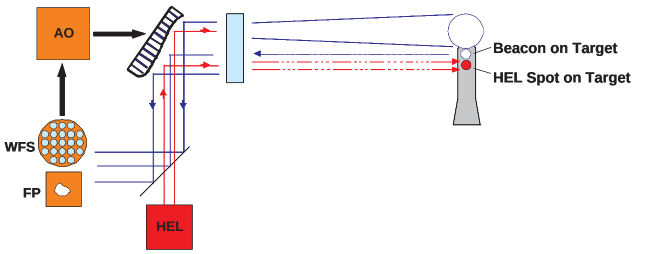

Fig. 1. Diagram of an adaptive optics problem in directed energy weapons. Key components of the control system: adaptive optics algorithm (AO), deformable mirror (DM), wavefront sensor (WFS), high energy laser (HEL).

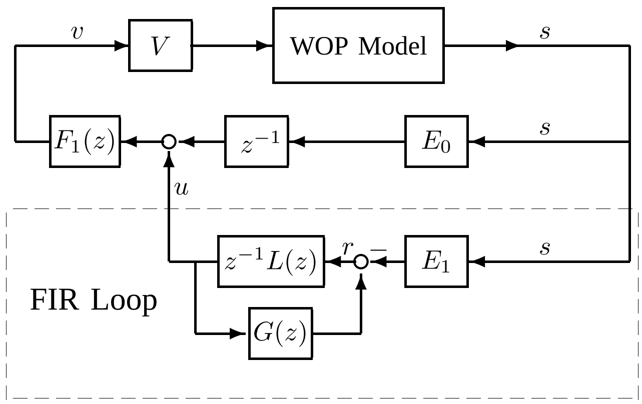

Fig. 2. Block diagram for adaptive optics.

illuminating the target with a low energy laser as the basis for determining the commands to the deformable mirror required to cancel turbulence-induced phase distortion. Because the beacon is considered to be a distant point source, the wavefront propagating from the beacon would be very nearly a plane wave when it reached the mirror with no atmospheric turbulence. This plane wave is the desired set point for the control algorithm. If the wavefronts propagating from the beacon and to the target travel through approximately the same atmosphere, then correcting the wavefront from the beacon should compensate for the turbulence effects on outgoing beam.

For control purposes, the adaptive optics problem is represented by the block diagram in Figure 2. The measured wavefront slope vector is denoted by s. Since the wavefront cannot be measured directly, the objective of the control loops is to minimize the RMS value of the projection of s onto a certain subspace. The top feedback loop is a classical AO loop, so that is linear and time-invariant (LTI). The matrix V represents a parameterization of actuator space [11]. The actuator command vector c and the control command vector v are related by

$$c = V v \,. \tag{1}$$

The matrix $\tilde{\Gamma}$ is given by

$$\tilde{\Gamma} = \Gamma V \,, \tag{2}$$

where Γ is the poke matrix. Thus,

$$\tilde{\Gamma} v = \Gamma c \,. \tag{3}$$

The reconstructor matrix E_0 is equal to the pseudo inverse of $\tilde{\Gamma}$, so that

$$E_0 \tilde{\Gamma} = I \,. \tag{4}$$

The objective of the control loops is to minimize the variance of the part of the wavefront reconstructed by E_0; i.e., the part of the wavefront in the range space of E_0.

The z^{-1} in each control loop represents a one-step delay due to sensor read-out and computation. Hence, latency in the adaptive optics problem considered in this paper is one time step.

The block labeled WOP (wave optics propagation) Model in Figure 2 is a high-fidelity simulation of a directed energy problem like that represented in Figure 1. This model includes the wave optics propagation of both the beacon and high energy laser beams, as well as models of the wavefront sensor and deformable mirror, and focal plane imaging on both the adaptive optics platform and the target. This wave optics model is contained in the program WaveTrain, which is a product of MZA Associates Corporation. The model used in this research is based on non-sensitive features of HEL systems.

III. The Control Loops

A. *Classical AO Loop*

The linear time-invariant (LTI) feedback control loop (the top loop in Figure 2) is a classical AO loop. It contains the reconstructor matrix E_0 and the digital integrator

$$F_1(z) = K_1 \frac{z}{z-1} \,, \qquad K_1 = 0.5 \,, \tag{5}$$

along with the one-step computation delay.

B. *FIR Loop*

The quasi-adaptive control loop is labeled "FIR Loop" in Figure 2 (enclosed in the dashed box). This control loop augments the classical AO loop to enhance wavefront prediction and correction, particularly for higher-order wavefront modes. The main component of this loop is the FIR filter $L(z)$. The gains in this filter are updated adaptively. This adaptation may be either fully adaptive (i.e., at each time step) or quasi adaptive (i.e., periodically). In the simulations for this paper, the FIR gains were identified in the quasi adaptive fashion from data collected over one second (5000 frames)e.

For identification of the FIR gains, the problem is formulated as a feedforward noise-cancellation problem with tuning signal e and reference signal r. From Figure 2,

$$r = E_1 \, s \,. \tag{6}$$

In the FIR loop, $E_1 = E_0$ in this paper, although the methods are extended easily without this condition. The *tuning signal* for the FIR filter is the sequence

$$e = E_0 s\,; \tag{7}$$

i.e., the FIR gains are identified to minimize the variance of e. The transfer function from the control signal u to the signal e with only the classical AO loop closed is represented by $G(z)$. Of course, only an estimate of this transfer function is available in applications.

The filter L could be either FIR or IIR. While an IIR filter theoretically would produce optimal steady-state performance for stationary disturbance statistics, an FIR filter of sufficient order can approximate the steady-state performance of an IIR filter, and the convergence of the adaptive algorithm for an FIR filter is more robust with respect to modeling errors. In most adaptive optics problems to which the current methods have been applied, FIR filter orders greater than four do not offer further performance improvement. Hence, an FIR filter is used in this paper. As the gains in the filter L are updated repeatedly, and they converge to optimal constant gains when the disturbances have constant statistics.

The least-squares objective for choosing the filter matrix $L(z)$ is to minimize $e^T(t)e(t)$. An important result of the parameterization of actuator and sensor spaces in [7], [8], [11] is that each component of $e(t)$ is affected only by the corresponding component of the control command vector v. This means that the RLS problem reduces to a set of independent RLS problems for the gains in the individual rows of $L(z)$.

A challenging feature of the problem here is the very large number of channels. Even though the parameterization of actuator and sensor spaces causes the channels in the signals v, u, and e to remain uncoupled, all channels in the noise reference r feed into each control command. Hence, the adaptive filtering problem to determine the optimal gains for $L(z)$ is multichannel. An on-line algorithm for adaptively determining the filter gains must be numerically robust in the presence of many channels. The algorithm proposed here is a multichannel adaptive lattice filter, which is based on the algorithm presented in [10].

IV. SIMULATION RESULTS

Simulation of a problem like that illustrated in Figure 1 were performed. The high-fidelity wavefront propagation code WaveTrain simulated the effect of atmospheric turbulence on the laser beams, was wells as the optics hardware (deformable mirror and wavefront sensor). The deformable mirror in this simulation has 196 master actuators, and the Hartmann wavefront sensor had 156 subapertures. For the simulation results presented here, the beacon for adaptive optics was a point source. In current research, the control methods used here are being applied to simulations with extended beacons.

The FIR filter had order 4. Initially, closed-loop wavefront sensor data was generated with only the top AO loop closed. This data was used by the lattice filter to identify the FIR gains. Then the simulation was started, with a different random seed for turbulence generation, with the FIR loop closed and run for 5000 time steps to produce the results shown in the figures here.

Point spread functions were computed for simulations with no control, with the LTI feedback control loop only, and with the feedback loop augmented by the adaptive loop. The point spread functions then were averaged over 50-point intervals to simulate a shutter speed that is $1/100$ of the control sample-and-hold rate of 5000 Hz. Typical PSFs, along the corresponding images of the beacon, are plotted in Figure 3. The diffraction-limited Strehl ratio was normalized to 1. Figure 4 shows the on-target high-order Strehl ratios for the last 2000 time steps. The high-oder Strehl ratio is the normalized intensity at the centroid of the image. The mean value of the high-order Strehl ratio is 80% greater with the FIR loop than with the standard AO loop only.

Perhaps the single most important performance measure for a directed energy system is the maximum accumulated energy on any single point on the target. Figure 3 shows the maximum accumulated intensity with the FIR loop is 69% greater with the FIR loop than with the standard AO loop only. the normalized accumulated intensities at all target pixels, with and without the FIR augmentation to the standard AO loop. These distributions were computed by averaging the on-target image over the 5000 frames (one second) of each simulation. The maximum accumulated intensity is 69% greater with the FIR loop than with the standard AO loop only.

V. CONCLUSIONS

The quasi adaptive FIR control loop produces significant improvement in the point spread function of the adaptive optics system. The results here have been achieved for a significantly more challenging adaptive optics problem, and a more realistic simulation model, than those used in previous studies to illustrate the effectiveness of augmenting a classical adaptive optics loop with adaptive filtering and control because the simulation here used an extended turbulence path, rather than the relatively short turbulence paths common in astronomy applications. Also, the new configuration of the adaptive loop here, which uses only the closed-loop wavefront sensor vector as input to the adaptive loop, has advantages for practical implementation.

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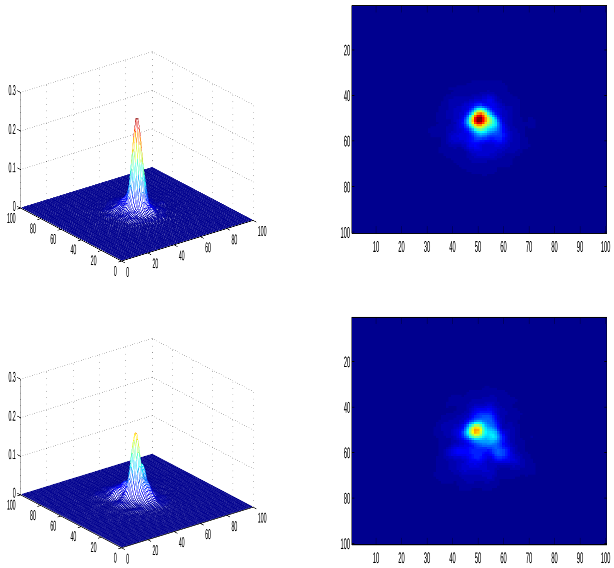

Fig. 3. Point spread functions (left) and images (right) for 50-point interval ending at time step 5000. Top: standard AO loop augmented by FIR loop (194 channels); Bottom: standard AO loop only (194 channels).

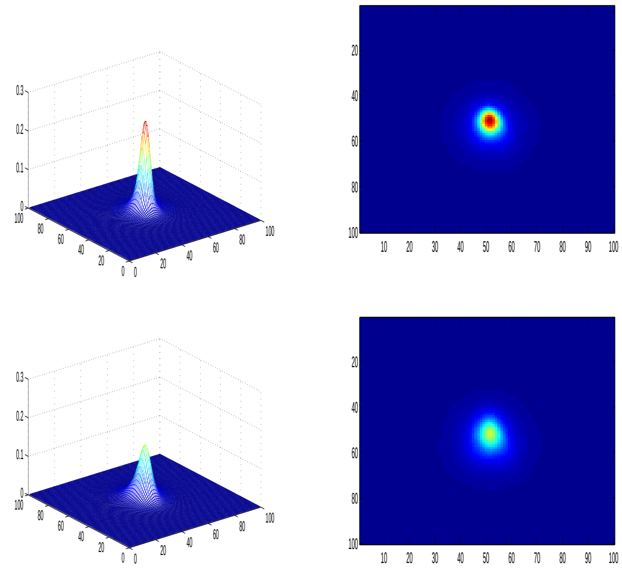

Fig. 5. Long term averaged point spread functions (left) and long term images (right) for 5000 time steps. Top: feedback loop with FIR loop (194 channels); Bottom: standard AO loop (194 channels).

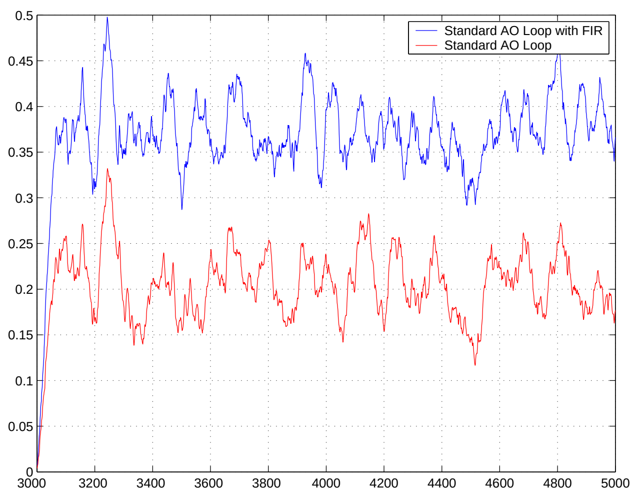

Fig. 4. High-order Strehl ratio time histories for point spread functions averaged over 50-point intervals.

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