UCRL-JC-128432
PREPRINT

Tip-Tilt Correction for Astronomical Telescopes using Adaptive Control

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This paper was prepared for submittal to the
Wescon - Integrated Circuit Expo 1997
Santa Clara, California
November 5-6, 1997

April 17, 1997

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Livermore
National
Laboratory

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Abstract The greatest hindrance to modern astronomy is the effect of the Earth's atmosphere on incoming light. The fundamental, or lowest mode of disturbance is tip and tilt. This mode causes the focused image of a distant point source to move about in a plane (X-Y motion) as viewed from a telescope objective. Tip-tilt correction systems can be used to correct for these disturbances in real time. We propose a novel application of adaptive control to address some unique problems inherent with tip-tilt correction systems for astronomical telescopes.

Overview

Atmospheric Disturbance

Adaptive optic (AO) systems are used to correct for atmospheric disturbances in real time. Figure 1 is a spatial plot of an image of a star on a CCD array, showing performance typical[1] of AO systems. The high-order modes, which tend to make the image large and blurred, are typically corrected with a multi-actuator deformable mirror[4], while the tip-tilt component is generally corrected with a high speed two axis steering mirror, primarily due to the large dynamic range needed compared to higher order modes.

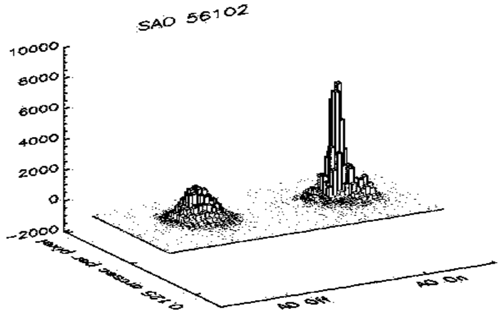

Figure 1 AO system performance

Figure 2 is a simplified diagram of an astronomical telescope with adaptive optics.

Tip-tilt correction Fundamentally, to correct for tip-tilt motion, a tip-tilt, or two dimensional position sensor (usually a four quadrant detector, or "quad cell") is placed at a focal point, and with the application of an appropriate control law, a correction is applied to a steering mirror.

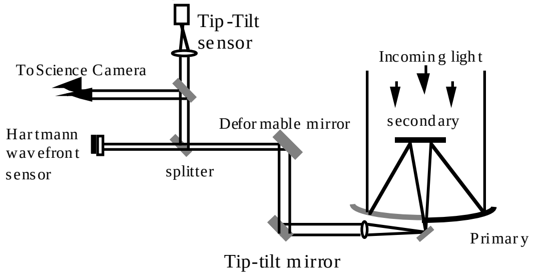

Figure 2 Adaptive optics in astronomy

A tip-tilt system of this type is being developed by the author and others at Lawrence Livermore National Laboratory for the 10 meter Keck II telescope in Hawaii.

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[1] Preliminary data from LLNL/Lick observatory Laser Guide Star experiment Sept96

The tip-tilt sensor must respond to extremely low light levels, and uses four discrete avalanche photo diodes arranged as a quad cell. The sensors have 80% quantum efficiency (typical), thus generating a TTL pulse for 80% of the photons that strike it. The mirror is 8 inches in diameter fabricated from lightweight silicon carbide and is translated with three linear piezoelectric actuators. The range of the mirror is approximately 500 microradians, and the necessary control bandwidth is on the order of 100Hz.

Project Definition

We propose a novel application of adaptive control to address some unique problems inherent with the system outlined in figure 2. The purpose of this project is to study adaptive control methods with the aid of MATLAB, build a simplified system capable of demonstrating the functionality of classical fixed gain control systems, and subsequently demonstrate performance of adaptive control methods.

Motivation for Adaptive Control

The apparent sensitivity of the position sensor is proportional to light intensity and the size of the beam striking it. Division of the error signal by the sum of all four quadrants normalizes for changes in intensity, but the sensor is still sensitive to the diameter of the beam incident upon it. Spot size on the sensor is affected by changing atmospheric, or "seeing" conditions, different telescope configurations, and the operation of higher order adaptive optic systems, namely the deformable mirror. The performance of the tip-tilt correction system can be compromised by changes in sensitivity, or "gain" of the sensor. The system can be optimized for a small spot (maximum gain while maintaining stability), but the controller performance will be compromised if the size of the spot becomes larger. Thus, the system can be categorized as linear, time variant (LTV). An adaptive control system is appropriate for this application.

Control law choice The atmospheric disturbance is band-limited[2] and small relative to system modeling errors and with a further stipulation that the system need not operate with exceptionally poor signal-to-noise ratio (S/N)[3], we can make the assumption that the system is deterministic. Derivation and application of adaptive control to deterministic systems is relatively straightforward and far simpler than for stochastic systems[1] . The approach we use is to implement a system with both fixed-gain and adaptive feedback paths to provide additional flexibility.

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[2] The tilt spectra of the atmosphere is most often described by a Kolmogorov spectrum, described in[4]

[3] The Keck system will have settable integration times (count periods for the photon counters) to optimize S/N vs disturbance rejection bandwidth for different conditions

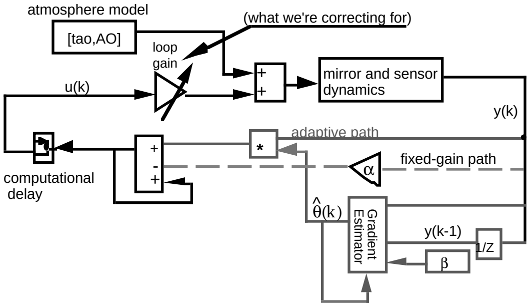

Figure 3 block diagram of system model

The implemented control law algorithm has the added benefit of providing improved initial transient performance with a proper choice of both loop gains. Figure 3 is a block diagram of the system model. For the adaptive path, a simple gradient projection algorithm[1] is used to provide on-line parameter estimation. The gain of the projection algorithm does not go to zero, and can thus track time-varying systems. The parameter estimator is given by:

$$\hat{\theta}(k) = \hat{\theta}(k-1) + \frac{\beta y(k) y(k-1)}{c + y(k-1)^2} \qquad (1)$$

with the control law implemented as:

$$u(k) = u(k-1) + (\hat{\theta}(k) - \alpha) y(k) \qquad (2)$$

where α is the fixed gain component.

System modeling

The Matlab / SIMULINK®[2] environment was used extensively to develop models of fixed-gain and adaptive control techniques. The "baseline" model used for comparison is an existing tip-tilt system designed by the author and fielded at Lick observatory above San Jose, CA. This system employs an analog realization of a type II (double integrator) controller of the form:

$$\alpha(s) = \frac{s+\omega_n}{S^2+2\xi\omega_d S+\omega_d^2} \qquad (3)$$

The analog system can be conveniently characterized with standard frequency-domain techniques, however classical Bode and small signal linearization methods cannot be used to accurately represent adaptive systems. An ensemble of MATLAB functions utilizing band-limited random noise, FFT techniques, and time domain averaging was assembled to study and optimize the adaptive controller.

Modeling results Figure 4 shows a two second sample of simulated tip-tilt data (1), a simulated gain which is a function of time (2), and the residual error from the fixed-gain (3) and adaptive (4) models. The fixed-gain controller is set to be stable at the highest loop gain, and as shown in figure 4, has a larger residual error when the loop gain is lower (5). Note that the only significant perturbation in the adaptive system is when there is a step increase in gain (i.e. when the higher order adaptive optics system is activated). This transient event is an artifact of the parameter estimator (the projection algorithm), as algorithms of this type typically have poor transient response. This presents no problem, as data is not generally collected during such transient events.

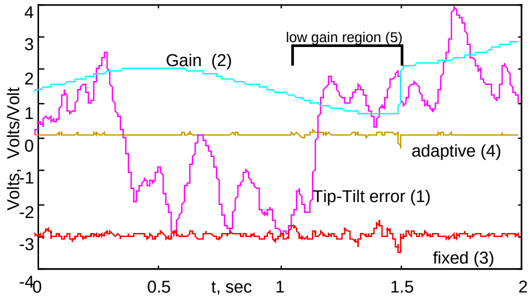

Figure 4 Performance of fixed-gain and adaptive techniques

A novel result of adaptive gradient projection is that there is no gain region so disturbances at any frequency are not amplified. The frequency at which the controller stops rejecting can be manipulated by adjusting parameters in the controller. This allows the controller to be configured for different S/N conditions[3]. Figure 5 shows disturbance rejection for the two controllers. The data was generated using a transfer function estimate[3] operating on time domain data generated while varying the loop gain, as in figure 4. The noise in the estimates is resultant from random-phase errors inherent in the characterization technique. Note the gain region between 200 - 400Hz for the fixed gain controller.

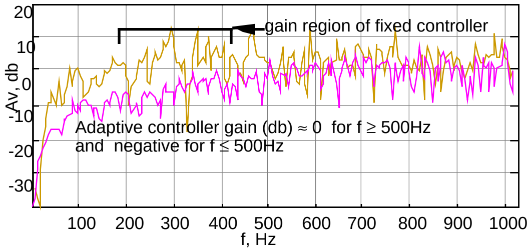

Figure 5 Disturbance rejection

Gain in this region can have a negative impact on performance under poor S/N conditions.

System structure

In parallel with the modeling effort, a simplified system was assembled to verify modeling results. The sensor is a lateral photo effect diode, and a piezoelectric tilting stage is used to steer a 50mm mirror. Much of the electronic hardware will be duplicated for the Keck system, including the VME-based 68040 microprocessor, A/D and D/A converters, and high current drive electronics for the actuator. The control software is implemented in ANSI C, developed under Microware's OS-9® real-time operating system. Figure 6 is a diagram of the system.

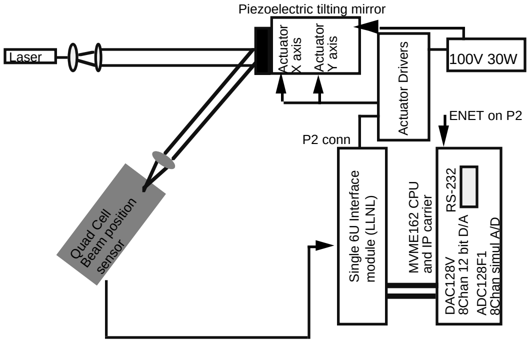

Figure 6 Controller hardware block diagram

Results and future work

Preliminary observations of fixed-gain and adaptive controller implementations are very much in line with model predictions, including disturbance rejection measurements. Adaptive performance was qualitatively verified by making static changes (in software) to the gain applied to the sensor input, and comparing the fixed and adaptive controller performance. RMS residual error for the constructed system was determined by applying the output of the position sensor (analog) to RMS-DC converters. For the models, this was accomplished by simple time domain averaging functions. In particular, band-limited white noise was injected at the steering mirror and RMS position was measured open and closed loop. For one set of controller parameters, the fixed gain controller produced a factor of 10-15 reduction in overall RMS motion with high sensor gain, and a factor of 5 when the gain was decreased by a factor of three. The adaptive controller produced a more solid factor of 15 reduction at high gain, and a small (< 10%) but detectable reduction in overall RMS error when the gain was dropped by a factor of three. Experimental parameter optimization and more formal characterization is scheduled for the near-term. The Keck system will likely be implemented with both algorithms, with the fixed-gain path of the *adaptive* controller used as a default(i.e. $\alpha = k$, $\beta = 0$).

References

[1] Goodwin, Sin *Adaptive Filtering, Prediction, and Control 1984* New Jersey: Prentice Hall ISBN 0-13-004069-X

[2] The Mathworks, Inc. 24 Prime Park Way, Natick, Mass 01760

[3] Krause, Shure, Little. *Signal Processing Toolbox Third printing.* The Mathworks, Inc. 24 Prime Park Way, Natick, Mass 01760

[4]Tyson, Robert K. *Principles of Adaptive Optics 1991* Boston: Academic Press, Inc. ISBN 0-12-705900-8

Acknowledgements The author is employed by Lawrence Livermore National Laboratory (LLNL), and currently supports the Laser Guide Star program. He is currently pursuing an engineering degree at the University of the Pacific. The author is a member of an LLNL team who have successfully developed an AO system at Lick Observatory above San Jose, CA utilizing the world's first laser driven sodium-layer guide star.

The LLNL team, along with the California Association for Research in Astronomy (CARA) are currently designing a laser and AO system to be installed on the Keck II telescope in Hawaii.

The option to use an adaptive controller for the tip-tilt subsystem was first proposed by the author at a 1995 preliminary design review.

This work performed under the auspices of the U.S. DOE by LLNL under contract no. W-7405-Eng-48.

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