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Final Report

ADAPTIVE FILTERING AND SYSTEM IDENTIFICATION

AFOSR GRANT F-49620-03-1-0234

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Abstract

The primary objectives of this project are to develop new real time algorithms for adaptive filtering, prediction, and system identification with improved efficiency and numerical stability for the large numbers of channels and high filter orders typically required in Air Force applications such as adaptive optics, laser communications, target tracking and image processing. The research supports research and development at the Air Force Research Laboratory on directed energy weapons and laser communications. The advanced tactical laser (ATL), the airborne laser (ABL) and similar weapons systems are the primary Air Force programs motivating the research. Additional application areas include optical wireless communication systems, blind identification and deconvolution in wireless communications, and active control of noise and vibration. This report discusses recent collaborations with the Air Force Research Laboratory (AFRL) and industry.

Control of Laser Beam Jitter

Control of laser beam jitter has become increasingly important in directed-energy systems like the Airborne Laser (ABL) and Advanced Tactical Laser (ATL), as well as in wireless optical communications, which have both commercial and military applications. The most important sources of laser beam jitter are platform (aircraft) vibration and atmospheric turbulence. Jitter typically has multiple narrow-band components, often combined with broadband disturbance. The frequency content of jitter varies as different platform modes are excited and different atmospheric conditions are encountered. Hence the need for adaptive jitter control. No linear-time-invariant (LTI) controller can control all disturbance bandwidths optimally. By adapting to the particular frequency content of any disturbance, adaptive control effectively extends the bandwidth of even robust high-performance LTI feedback controllers like the -synthesis controller used in the experiments reported here.

We have applied lattice filter based subspace system identification and adaptive control algorithms to beam steering experiments at UCLA [1, 2, 3, 4, 5, 6]. This work has demonstrated the enhanced disturbance rejection achievable in laser beam steering by modern optimal feedback controllers augmented by adaptive control loops that determine control gains that are optimal for the current disturbance acting on the laser beam. In our adaptive loops, an adaptive lattice filter implicitly identifies the disturbance statistics from real time quad cell data.

The most important recent advances in jitter control have been the development of a method for variable-order adaptive control [4, 6], comparison of experimental performance to theoretical optimal performance [6, 3], a method for frequency weighting in adaptive control [5] and adaptive control of a new class of liquid crystal beam steering devices [7, 8, 9]. The structure of the adaptive controller is based on the order-recursive structure of RLS lattice filters, as shown in Figure 3. Because of this property, the lattice filter automatically generates optimal adaptive controllers of all orders up to some maximum order N (with no additional computation).

Variable-order adaptive control is important because optimal steady-state performance usually requires a high-order controller, but higher-order controllers require more data for adaptive identification of optimal gains; hence, high-order controllers produce slower adaptation and often large transient responses if the adaptive loop is closed before near-optimal gains are identified. Since the few gains for low-order control laws can be identified from small numbers of data points, low-order control laws yield very fast adaptation without generating large transients.

Laser Beam Control with a New Liquid Crystal Device

UCLA, AFRL and Teledyne Scientific Co. have collaborated to apply feedback and adaptive feedforward control to Teledyne's new liquid crystal beam steering devices [7, 8, 9]. These novel beam steering devices are being developed as actuators in jitter control and adaptive optics for applications to laser weapons and laser communications. Compared to standard mirrors used for beam control, the liquid crystal devices have the advantages of low power consumption and no moving parts.

Figures 1 and 2 show UCLA's beam control experiment with the prototype liquid crystal device. Figures 3 and 4 show the block diagrams for the model of the liquid crystal device and the control system. An important question about the new devices is, can they deliver the control bandwidths comparable to those of fast steering mirrors? The experimental results in Figure 5 from [7] for a prototype device and more extensive experimental results in [8] are quite positive.

UCLA's adaptive control loop had to be modified to handle nonlinearities in the liquid crystal device resulting from a rate limit and quantization effects. Such nonlinearities have not been encountered in our research with fast steering mirrors [1, 2, 3, 6, 4, 5], but our newest adaptive control design accommodates the nonlinearities, resulting in no apparent performance degradation.

The close collaboration among UCLA, AFRL and Teledyne Scientific Co. has been very productive in several ways. First, the collaboration has illustrated the benefits of integrating considerations of control system performance into hardware design. Teledyne based the re-design of the driver for the two-axis device partly on the performance of an earlier single-axis device in control experiments at UCLA. The resulting two-axis device allowed the adaptive control loop to achieve much higher bandwidths than with the initial device. Second, UCLA students and faculty have had the opportunity of working with an exciting new class of hardware being developed in industry for Air Force missions. The experimental results reported in [7, 8, 9] were obtained from a jitter control experiment in UCLA's beam control laboratory with the Teledyne liquid crystal device. Most recently, UCLA Ph. D. student Pawel Orzechowski has worked with AFRL and Teledyne researchers to set up a similar experiment at the Starfire Optical Range, and we plan to continue this collaboration.

While significant questions remain about the use of liquid crystal devices in HEL beam control systems, it appears likely that careful system identification of the liquid crystal device will produce better dynamic models that will allow adaptive and optimal control loops to achieve even greater bandwidth.

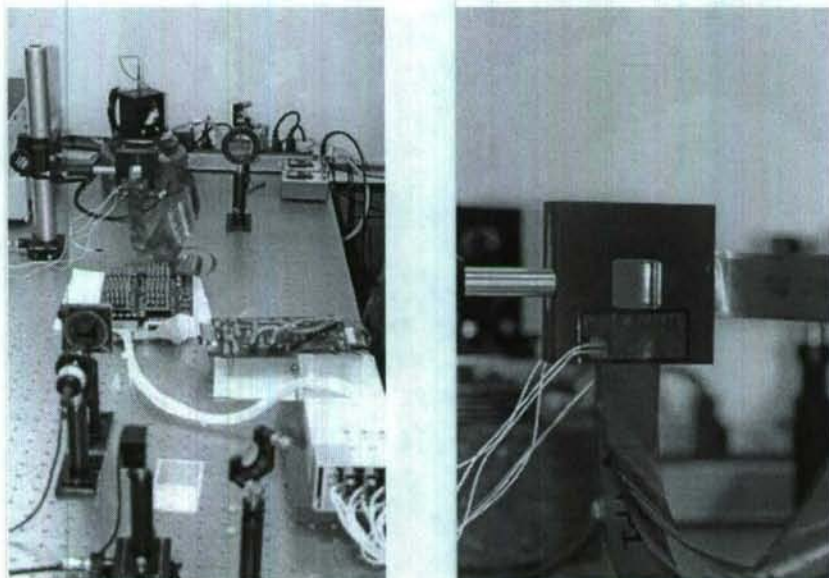


Figure 1: Left: UCLA beam control experiment with Teledyne's prototype liquid crystal beam steering device. Control sample and hold rate = 3125 Hz. Right: Zoomed-in view of the liquid crystal device.

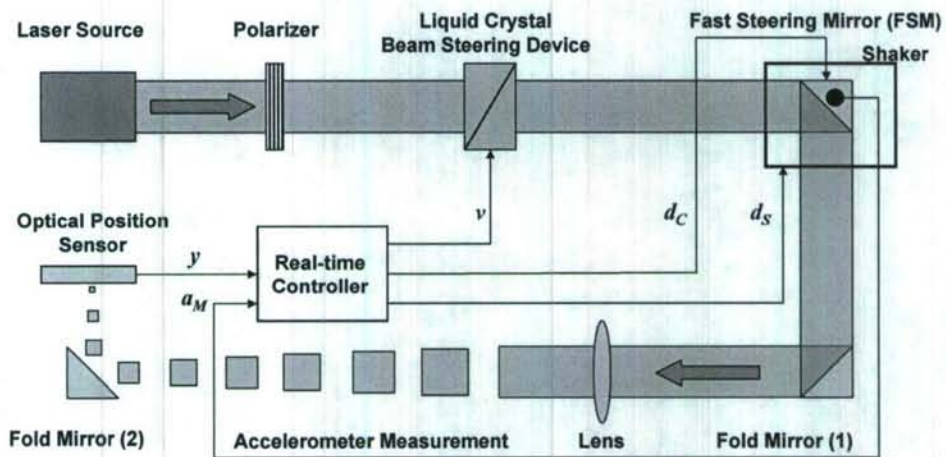


Figure 2: Diagram of UCLA beam control experiment with Teledyne's liquid crystal beam steering device.

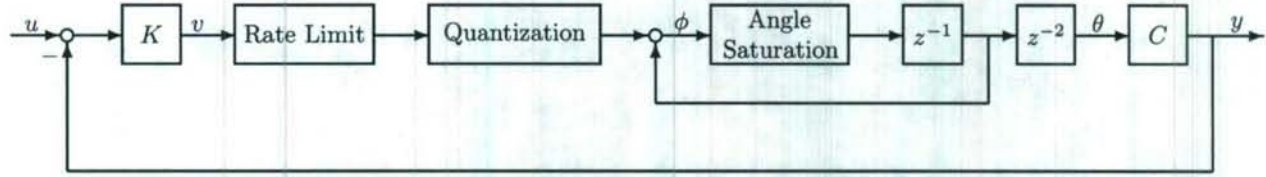


Figure 3: Block diagram of the liquid crystal device and LTI feedback control loop. The signals (all two-dimensional): y = measurement vector from optical position sensor, θ = beam angle vector, v = net control command before saturation and quantization, u = feedforward adaptive control command. Constant matrices: K = diagonal feedback control gain, C = diagonal matrix of conversions factors.

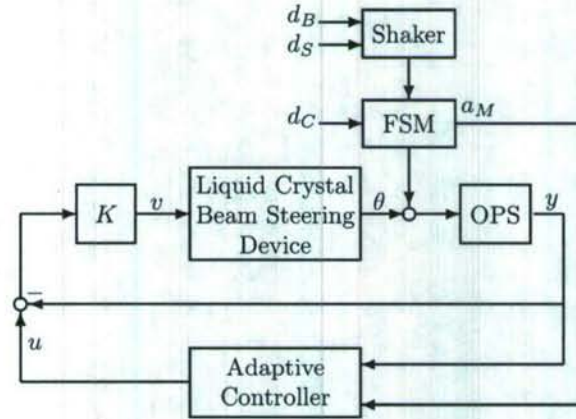


Figure 4: Block diagram of the control system. d_S = disturbance command to shaker; d_B = building vibration; d_C = disturbance command to FSM; d_M = response of FSM; θ = beam angle from liquid crystal beam steering device; y = beam position; OPS = optical position sensor; u and v = control commands.

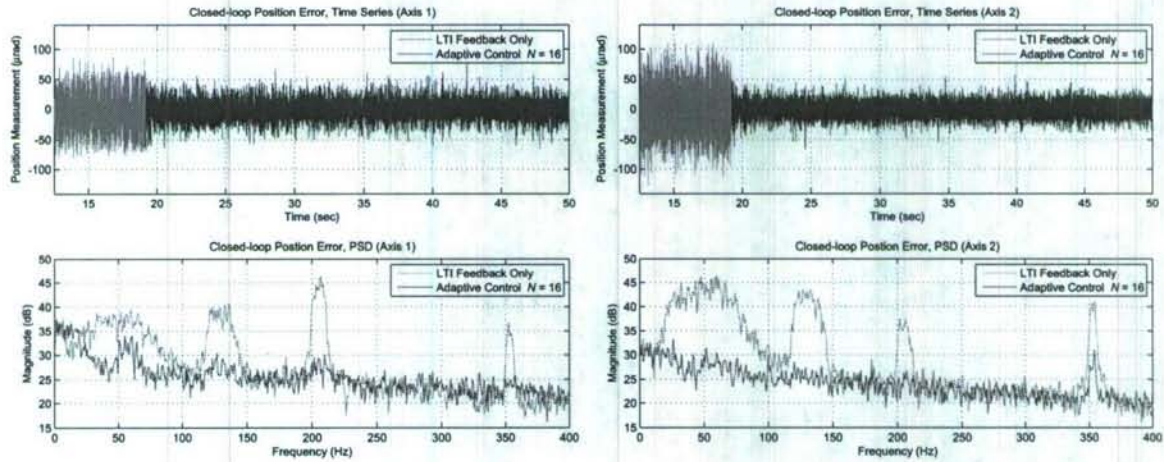


Figure 5: Disturbance rejection performance comparison for the horizontal axis (Axis 1) and the vertical axis (Axis 2). LTI feedback control (red); adaptive control (blue). Maximum lattice filter order $N = 10$. Disturbance sources: fast steering mirror (FSM) and building vibrations.

Adaptive Control and Filtering in Adaptive Optics

UCLA and AFRL researchers have demonstrated a new adaptive control scheme for adaptive optics in experiments in the Atmospheric Simulation and Adaptive-optics Laboratory Testbed (ASALT) at the Starfire Optical Range at the Air Force Research Laboratory, Directed Energy Directorate, Kirtland AFB. The adaptive control scheme was developed at UCLA in collaboration with researchers at the Air Force Research Laboratory. Initial results from this collaboration were presented in [10].

Figure 6 shows a schematic diagram of the ASALT optical system. As shown in Figure 7, the adaptive control loop augments a classical AO loop to enhance beam control and imaging through turbulence. High-fidelity wave-optics simulations of directed energy systems have shown significant improvement in Strehl ratio (i.e., on-target intensity) and tracking jitter, and such enhanced performance now has been confirmed by the first experimental application of the new methods [10].

Experiments were performed in the ASALT laboratory to evaluate the performance of the quasi-adaptive version of the adaptive control loop. In the experiments, the first 150 modes from a set of frequency-weighted deformable-mirror modes were used by the adaptive control loop [10]. First, 3000 wavefront sensor frames were used to identify the adaptive filter gains, and then the performance of the adaptive controller was evaluated on 1000 frames independent of those used for identification.

For comparison, the same experiment was performed with only the classical AO and track loops, using the same 1000 frames for evaluation. For the turbulence scenario examined, the adaptive controller provided a nearly 50% increase in Strehl ratio and reduced the variability by more than 15%. Figure 8 shows example images from the evaluation sequences, further demonstrating the benefits of the adaptive controller.

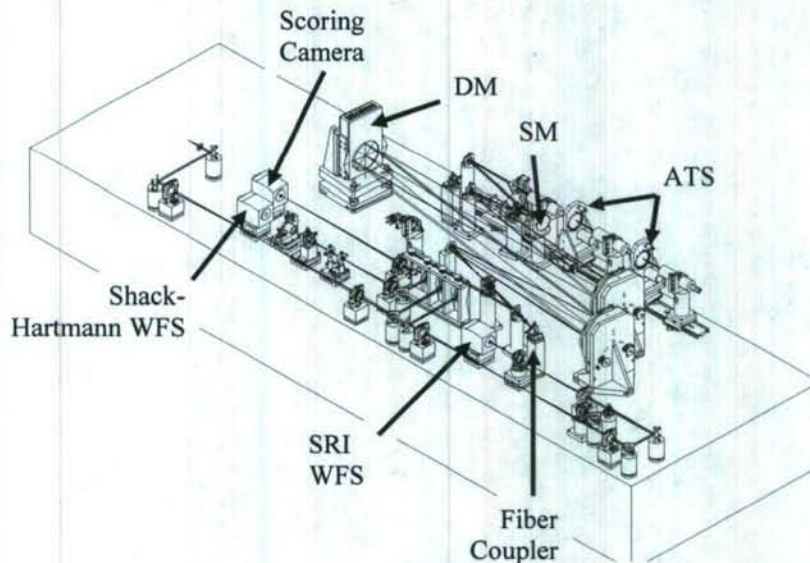


Figure 6: Atmospheric Simulation and Adaptive-optics Laboratory Testbed (ASALT) optical system, Starfire Optical Range, Kirtland AFB. The Self-Referencing Interferometer Wavefront Sensor (SRI WFS), an innovative sensor being developed at the Starfire Optical Range, was used for the experiments described.

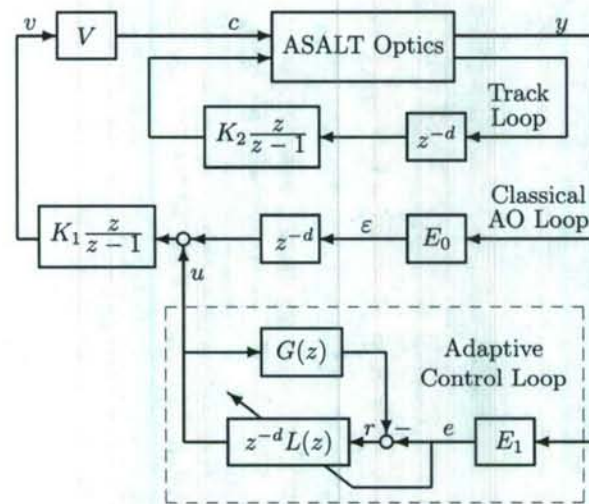


Figure 7: Block diagram of the digital control loops for adaptive optics. ASALT optics block represents the optical system in Figure 6.

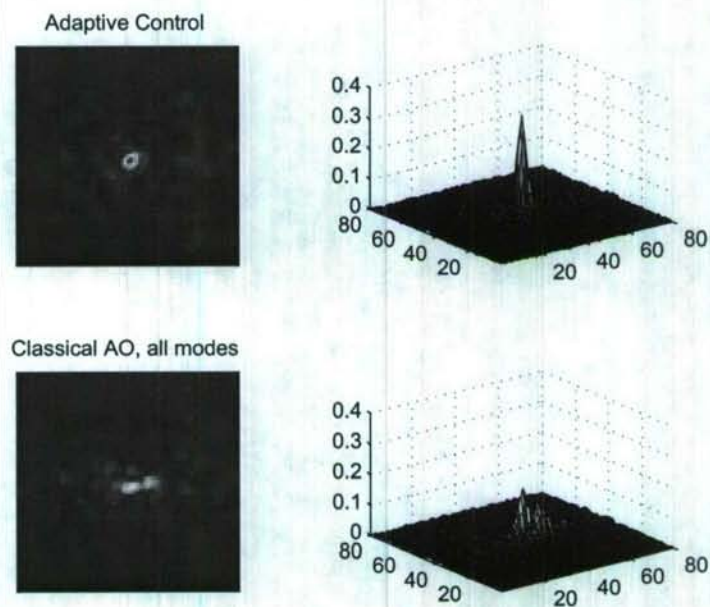


Figure 8: Representative closed-loop scoring camera images.

Personnel Supported

Graduate Students: Nestor Perez, Pawel Orzechowski
Post Doctoral Scholar: Neil Chen

Interactions

Professors Steve Gibson and T.-C. Tsao and graduate student Pawel Orzechowski have visited and collaborated extensively throughout the past year with several researchers at the Air Force Research Laboratory at Kirtland AFB, including Dr. Dan Herrick (505-853-5189), Dr. Darryl Sanchez (505-846-7209), Dr. Troy Rhoadarmer, Lt. Laura Klein and Lt. Robert Vincent. We also have collaborated extensively with Mr. Bruce Winker (805-373-4151), Dr. Milind Mahajan and Dr. Bing Wen of Teledyne Scientific Co. These contacts have focused on adaptive filtering and control for adaptive optics and control of jitter in laser beams.

Transitions

- UCLA is collaborating with Teledyne Scientific Company and AFRL, Kirtland AFB, to apply UCLA's adaptive jitter control algorithms with Rockwell's prototype liquid crystal devices for steering laser beams. This is a continuing collaboration with Dr. Dan Herrick of AFRL and Mr. Bruce Winker, Dr. Milind Mahajan and Dr. Bing Wen of Teledyne Scientific, which is funded by HEL JTO. Results have been reported in two papers and one Ph.D. dissertation [7, 8, 9], and more papers are planned.
- UCLA researchers are working with AFRL and Teledyne researchers to develop an experiment with Teledyne's liquid crystal device and UCLA's adaptive jitter control algorithms at AFRL's Starfire Optical Range, Kirtland AFB, under the direction of Dr. Dan Herrick.
- UCLA's adaptive control and filtering methods for adaptive optics have been implemented to improve beam control in the Atmospheric Simulation and Adaptive-optics Laboratory Testbed (ASALT) at the Starfire Optical Range at the Air Force Research Laboratory, Kirtland AFB. This is a continuing collaboration with Dr. Troy A. Rhoadarmer, Lt. Laura M. Klein of AFRL, Dr. Darryl Sanchez and Lt. Robert Vincent of AFRL. Results have been reported in one paper [10] and more are planned.
- UCLA's methods for adaptive control in adaptive optics are being used in a Phase II SBIR to MZA Associates Corporation for mitigation of aero-optics effects in directed energy weapons, funded by MDA. This work is lead by Dr. Matthew Whitely and colleagues at MZA Associates Corporation, Albuquerque, NM, and Dayton, OH.
- During the following year, UCLA's adaptive jitter control methods will be used in a relay-optics experiment at AFRL under a Phase II SBIR to Tempest Technologies, funded by MDA. This work is lead by Dr. Ben G. Fitzpatrick of Tempest Technologies, Los Angeles, CA.

References

- [1] P. K. Orzechowski, Tsu-Chin Tsao, and J. S. Gibson, "The effect of computational delay on performance of adaptive control systems," in *IMECE*. Chicago, IL: ASME, November 2006.
- [2] P. K. Orzechowski, J. S. Gibson, and Tsu-Chin Tsao, "Optimal jitter rejection in laser beam steering with variable-order adaptive control," in *Conference on Decision and Control*. San Diego, CA: IEEE, December 2006.
- [3] —, "Characterization of optimal FIR gains and minimum-variance performance for adaptive disturbance rejection," in *American Control Conference*. New York, NY: IEEE, July 2007.
- [4] N. O. Perez Arancibia, N. Chen, J. S. Gibson, and T.-C. Tsao, "Variable-order adaptive control of a mems steering mirror for suppression of laser beam jitter," *Optical Engineering*, vol. 45, no. 10, October 2006.
- [5] —, "Adaptive control of jitter in laser beam pointing and tracking," in *Proc. SPIE 6304, Free-Space Laser Communications VI*. San Diego, California: SPIE, September 2006.
- [6] P. K. Orzechowski, J. S. Gibson, and Tsu-Chin Tsao, "Optimal suppression of laser beam jitter by high-order RLS adaptive control," *IEEE Transactions on Control Systems Technology*, to appear.
- [7] Dan Herrick, P. K. Orzechowski, J. S. Gibson, Tsu-Chin Tsao, Milind Mahajan, and Bing Wen, "An alternative beam alignment approach for tactical systems," in *Directed Energy Systems Symposium: Beam Control Conference*. Monterey, CA: DEPS, March 2007.
- [8] P. K. Orzechowski, J. S. Gibson, Tsu-Chin Tsao, Dan Herrick, Milind Mahajan, and Bing Wen, "Adaptive rejection of optical jitter with a new liquid crystal beam steering device," in *Defense and Security Symposium*. Orlando, FL: SPIE, April 2007.
- [9] P. K. Orzechowski, "High-performance adaptive control of optical jitter in laser beam systems," Ph.D. dissertation, University of California, Los Angeles, 2007.
- [10] T. A. Rhoadarmer, L. M. Klein, J. S. Gibson, N. Chen, and Y.-T. Liu, "Adaptive control and filtering for closed-loop adaptive-optical wavefront reconstruction," in *SPIE Conference on Advanced Wavefront Control*, vol. 6306. San Diego, CA: SPIE, August 2006.

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