

MOEMS spatial light modulator development at the Center for Adaptive Optics

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ABSTRACT

The National Science Foundation Center for Adaptive Optics (CfAO) is coordinating a program for the development of spatial light modulators suitable for adaptive optics applications based on micro-optoelectromechanical systems (MOEMS) technology. This collaborative program is being conducted by researchers at several partner institutions including the Berkeley Sensor & Actuator Center, Boston Micromachines, Boston University, Lucent Technologies, the Jet Propulsion Laboratory, and Lawrence Livermore National Laboratory. The goal of this program is to produce MEMS spatial light modulators with several thousand actuators that can be used for high-resolution wavefront control applications that would benefit from low device cost, small system size, and low power requirements. The two primary applications targeted by the CfAO are astronomy and vision science. In this paper, we present an overview of the CfAO MEMS development plan along with details of the current program status.

Keywords: Center for Adaptive Optics, spatial light modulator, adaptive optics, astronomy, vision science

INTRODUCTION

The National Science Foundation (NSF) Center for Adaptive Optics (CfAO), headquartered at the University of California, Santa Cruz, is dedicated to “advancing and disseminating the technology of adaptive optics in service to science, health care, industry, and education [1].” Adaptive optics (AO) is a method for removing the blurring of images caused by changing distortions within optical systems. For example, turbulence in the Earth’s atmosphere causes blurring in astronomical images, and internal imperfections and fluids in the eye cause blurring in images of the retina. Adaptive optics applied to astronomy promises a spectacular improvement in resolution, by factors of 10 to 30. Large ground-based telescopes using AO can even exceed the performance of the Hubble Space Telescope and at much lower cost. Adaptive optics for vision science promises to correct the aberrations of the eye and to provide a powerful tool for understanding the structure and development of cones and rods in the living human retina. It also holds the promise of diagnosing tiny retinal defects before they become large enough to threaten a person’s vision.

Although adaptive optics was suggested for astronomical imaging in the 1950s, only today are the requisite technologies mature enough for AO to make an important impact. Adaptive optics systems require the marriage of several advanced technologies – precision optics, wavefront sensors, deformable mirrors, and lasers – all tied together by high-speed control systems. With recent developments in micro-electromechanical systems (MEMS) spatial light modulator (SLM) technology, adaptive optics systems have the potential to exceed performance specifications of conventional AO systems, while dramatically reducing cost, size, and power requirements. Typical conventional AO systems use bulk piezoelectric actuators to deform large glass plate mirrors which, as a rule of thumb, cost about \$1k/actuator. MEMS

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technology, while expensive in the development stage, offers the potential for spatial light modulators with thousands to millions of independently controlled pixels at a cost of less than \$1k per device. In this paper, we discuss the CfAO MEMS spatial light modulator development strategy, including applications targeted by the CfAO and the MEMS SLM specifications for each application, and we report on status of the CfAO MEMS program, now beginning its fourth year.

CfAO SCIENTIFIC THEMES AND MEMS DEFORMABLE MIRROR REQUIREMENTS

Going into its third year (2002), the CfAO reorganized into a structure with three scientific themes each with goals for MEMS development. The three themes are Vision Science, Extreme Adaptive Optics (ExAO), and AO for extremely large telescopes (ELT AO). The following gives a summary of each theme, and the MEMS requirements for each application.

Vision Science

Ophthalmic AO systems have been demonstrated in the laboratory for scientific research. The next horizon is to engineer compact, robust AO systems for use in clinics as well as scientific laboratories. The long-term goal is to commercialize a compact AO system for ophthalmic applications. Along the way, these new and existing AO systems will be used to advance our understanding of human vision, and to explore medical applications of adaptive optics. One of the instruments to be developed for vision science is a confocal scanning laser ophthalmoscope, which achieves high depth resolution as well as lateral resolution. This instrument will make possible high-resolution 3-D reconstruction of retinal blood vessels and of optic nerve fibers that carry signals to the brain.

Compact vision science instrumentation has been designed and is awaiting development of suitable MEMS mirrors. A MEMS deformable mirror targeting vision science applications must meet the following requirements: ~200 actuators, ~10 micron actuator range, greater than ~100 Hz operating frequency, less than ~20 nm surface quality, greater than ~97% fill factor, greater than ~80% reflectivity in visible and near IR, clear aperture ~10 mm in diameter, and unit cost ~\$1000. These requirements are tabulated in Table I. Liquid crystal spatial light modulators offer a potential alternative technology to MEMS deformable mirrors for this application.

Table I: MEMS deformable mirror requirements for three CfAO application areas.

CfAO Theme	Number of Actuators	Actuator Range	Operating Frequency	Surface Quality	Fill Factor	Reflectivity visible, IR	Aperture	Unit Cost
Vision Science	~200	~10 μm	> ~100 Hz	< ~20 nm	> ~97%	> ~80%	~10 mm	~\$1000
ExAO	~4000	~5 μm	> ~3kHz	< ~10 nm	> ~99%	~90%	~10 mm	<\$400k
ELT AO	~10,000	~5 μm	> ~3kHz	< ~10 nm	> ~99%	> ~95% UV – IR	~300 mm	<\$1M

Extreme Adaptive Optics

The ExAO theme is scientifically driven by the need to achieve high-contrast imaging and spectroscopic capabilities to enhance the detection and characterization of extra-solar planetary systems and their precursor disk material. By improving image quality, ExAO systems enable the detection of faint objects close to bright sources that would otherwise overwhelm them. This is accomplished both by increasing the peak intensity of point-source images and by removing light scattered by the atmosphere and the telescope optics into the "seeing disk". This combination of effects can dramatically improve the achievable contrast ratio for astronomical observations.

The primary goal of this theme is to catalyze the development of next generation high-order adaptive optics systems in order to achieve unprecedented capabilities for high-contrast astronomy. This will require activities in ExAO system design along with the design of instruments, such as coronagraphs, optimized for high-contrast observations. Additional crucial activities include the development of new simulation capabilities for ExAO systems and instruments, along with better characterization of existing high-order AO systems, and the development of new technologies in high-order wavefront correction devices, such as MEMS deformable mirrors, and in wavefront control system algorithms and architectures. Ongoing scientific utilization of high-contrast observational capabilities and development of data processing techniques optimized for high-contrast observations are also critical activities for this theme. The overall

goals for ExAO deformable mirrors are as follows: ~4000 actuators, ~5 micron actuator range (can be ~1 micron if cascaded with low order AO system), greater than ~3 kHz operating frequency, less than ~10 nm surface quality, greater than ~99% fill factor, greater than ~90% reflectivity in visible and near IR, clear aperture ~10 mm in diameter, and unit cost less than ~\$400k. These requirements are summarized in Table I. The time scale for development of the ExAO deformable mirror is two years and is contingent on co-funding and observatory selection. The Xinetics photonics module offers a potential alternative technology to MEMS deformable mirrors.

Extremely Large Telescope Adaptive Optics

The highest recommendation of the National Academy of Sciences' Astronomy and Astrophysics Survey Committee (2001) was the design and construction of a ground-based 30-meter telescope, equipped with adaptive optics – a giant segmented mirror telescope, or GSMT. Developing an adequate adaptive optics system for this telescope will be extremely challenging and will require developments in most technical areas of adaptive optics. Making a major contribution towards achieving this national priority is a natural and suitable objective for the CfAO. The benefits of multi-conjugate adaptive optics (MCAO) include widening the diffraction-limited field of view and achieving near-complete sky coverage with laser beacons (by overcoming the cone effect). While the ultimate implementation of an MCAO system for a 30-m telescope will require both time and resources far beyond the scope of the CfAO, we believe that we can develop the crucial concepts and components needed for its successful implementation. The overall goals for a MEMS DM designed to meet ELT AO objectives are as follows: ~10,000 actuators, ~5 micron actuator range, greater than ~3 kHz operating frequency, less than ~10 nm surface quality, greater than ~99% fill factor, greater than ~95% reflectivity in ultra-violet, visible, near and mid-IR, clear aperture ~300 mm in diameter, and unit cost less than ~\$1M. These specifications are listed in Table I. The time scale for meeting this objective is approximately 5-8 years, which is consistent with current ELT development plans, and is contingent on funding.

CfAO MEMS DEVELOPMENT PLAN

The original CfAO MEMS development plan was prepared at a workshop held in November 1999, based on input from the Berkeley Sensor & Actuator Center (BSAC), the Air Force Research Lab (AFRL), Boston University (BU), Boston Micromachines Corporation (BMC), Lucent Technologies, and Lawrence Livermore National Laboratory (LLNL). The main goals of this original plan were as follows:

1. Pursue two parallel designs for MEMS spatial light modulators by AFRL and BU that would demonstrate good optical surface quality (i.e., ~30 nm rms) with ~256 actuators having 1-2 micron range of motion.
2. Fabricate devices based on these designs at leading foundry facilities at Sandia National Laboratory (SNL) for the AFRL design and Cronos for the BU design.
3. Package devices and integrate with drive electronics in two parallel efforts at BMC and Lucent.
4. Deliver devices to LLNL for system testing and results assessment.
5. Iterate development steps 1-4 with larger formats, 1024 actuators on second iteration (Y3), 4096 actuators on third iteration (Y5).
6. Pursue a third independent development effort to fabricate high-stroke (~6 micron range) actuators integrated with single crystal silicon mirrors with excellent optical quality.

The CfAO MEMS development cycle is illustrated in Fig. 1. At the current time (beginning of Y4), 1024 pixel devices have been demonstrated, and projects are underway to develop MEMS SLMs with 4096 elements. Details of the development strategy and results are discussed below.

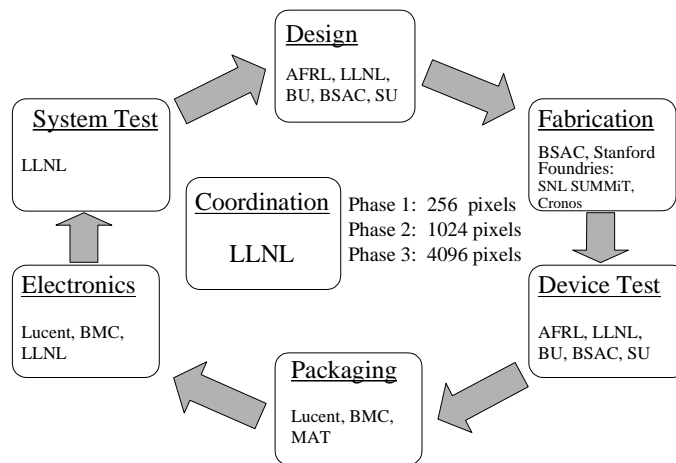


Figure 1:CfAO MEMS development cycle.

CfAO MEMS DEVELOPMENT STATUS

Boston University demonstrated a MEMS deformable mirror with 140 actuators that was fabricated at Cronos, packaged at BMC, integrated with BMC drive electronics, and delivered to LLNL for testing. Figure 2 shows an illustration and image of the BU device. The mirrors demonstrated good optical surface quality (30 nm rms) for devices with ~2 micron actuator stroke [2]. Boston University devices were also packaged at Lucent Technologies, integrated with Lucent drive electronics, and some testing was performed at Lucent.

A BMC 140 actuator deformable mirror was tested for vision science applications at the University of Rochester [3]. In addition, a BMC device was the basis for the design of an adaptive phoropter being developed as part of the CfAO vision science theme with support from the Department of Energy Biomedical Engineering Program. The 140 actuator BMC MEMS DM has 30 nm surface quality, greater than 97% fill factor, a low stress aluminum coating, 2 microns actuator range, 7 kHz operating frequency, a 3 mm clear aperture, and unit cost \$25k. Referring back to Table I, the device meets many of the requirements for Vision Science applications, although actuator range must be increased, and cost decreased.

Boston University and BMC have developed and are in the process of characterizing MEMS deformable mirrors with 1024 pixels [4]. The 1024 actuator devices, also fabricated at Cronos, were developed with support from the DARPA Coherent Communications, Imaging, and Targeting (CCIT) program. The devices were packaged at Lucent and shipped to LLNL where they were integrated with Lucent drive electronics. A working system was demonstrated with 1000 actuators, ~1 micron actuator range, ~30 nm surface quality, greater than 5 kHz operating frequency, greater than 97% fill factor, aluminum or gold coating, 9 mm clear aperture, and unit cost ~\$150k. These devices are close to meeting requirements for the ExAO theme (see Table I), although actuator range and surface quality must be improved, and the number of actuators must be increased from 1000 to 4000.

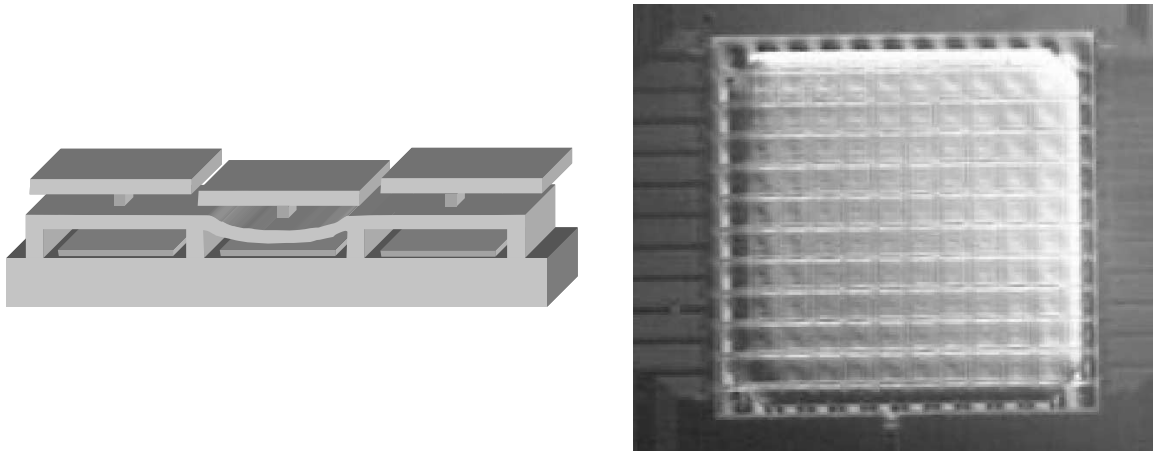


Figure 2: Illustration of the BU electrostatic actuator with segmented pixels (left) and a microscope image of a 12x12 pixel array (right).

An Air Force Research Laboratory device with 256 actuators fabricated the Sandia National Laboratory SUMMiT IV process, packaged at LLNL, and integrated with BMC drive electronics was tested at LLNL. The device demonstrated good optical surface quality except for some “print-through” features on the mirror surface.

Researchers at BSAC developed and demonstrated a MEMS device with 6 μm actuator stroke for hexagonal pixels with tip, tilt and piston motion, having very flat mirrors ($< 3 \text{ nm rms}$). The design features polycrystalline silicon/nickel composite flexures with residual stress gradient to elevate the actuators above the substrate surface, and electrostatic actuation with three electrodes to enable tilting (see Fig. 3). Single mirror pixels, and arrays of several actuators with mirrors were fabricated and tested at BSAC [5]. Operating frequency for these devices exceeded 1 kHz, and a fluidic self-assembly mirror bonding technique was demonstrated, enabling greater than 97% fill factor. A start-up company, IRIS AO, was formed to commercialize devices based on these designs for applications in vision science.

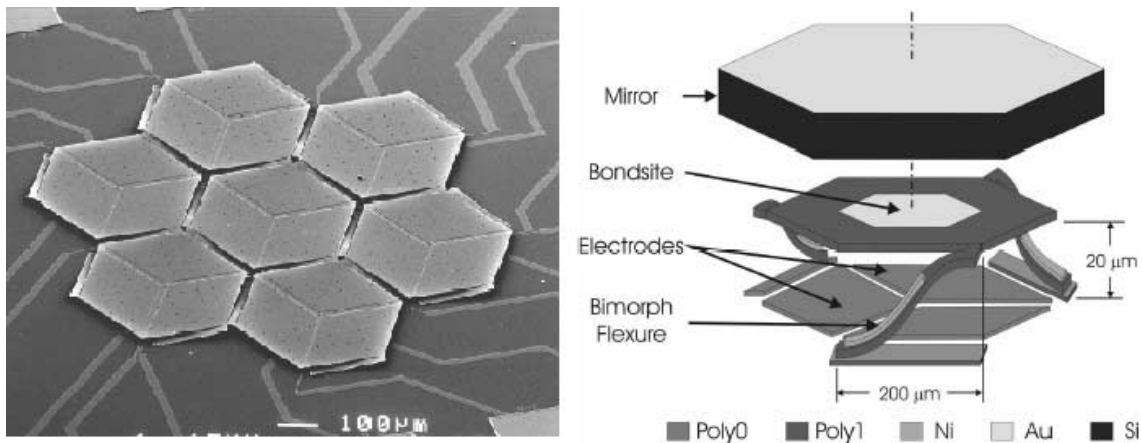


Figure 3: SEM of BSAC tip-tilt-piston biomorph actuator array (left) and sketch of actuator with assembled mirror (right).

An electret membrane mirror, which includes a permanent charge layer within the membrane and a transparent, top electrode, was conceived of at Lucent Technologies. Preliminary analysis of this design is discussed in [6]. By increasing the electrostatic pressure that may be applied to the membrane for a given operating voltage, an electret membrane may provide greater stroke than has been realized to date. Incorporating a transparent electrode with the membrane device allows electrostatic actuation in both directions along the optic axis (i.e. push and pull).

Lucent Technologies designed and fabricated low-tension membrane devices operating with traditional electrostatic actuation as milestones in the development of the electret membrane mirror. Membrane devices capable of 4.5 μm stroke have been fabricated with 256 and 1024 electrode actuators, as shown in Figure 4. Details are being presented at this conference [7]. In addition to fabrication, several of these devices have been packaged, wire bonded and tested for the CfAO using existing MEMS research infrastructure at Lucent Technologies.

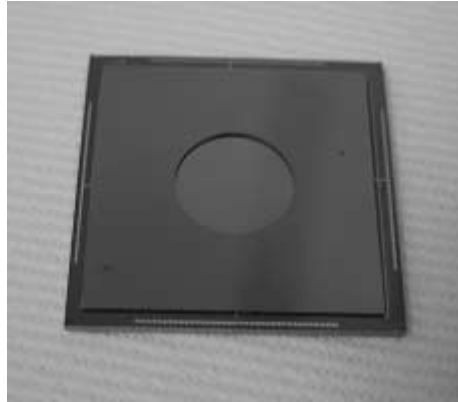


Figure 4: Membrane mirror device fabricated at Lucent Technologies. The device consists of a silicon membrane supported above an electrode plane with 256 actuating electrodes. 1024 electrode devices have also been fabricated.

For the ELT AO application, the various MEMS DM efforts were monitored, including Intellite, Stanford, Boston University, Lucent, BSAC, and JPL. Intellite, in collaboration with LLNL, demonstrated a process with close to a 100 mm clear aperture. The Jet Propulsion Laboratory is developing a large-stroke, continuous membrane, piezoelectric deformable mirror device, based on the membrane transfer technology, for space applications. The mirror technology at JPL is to support the requirements of several future space missions such as the ORIGINS missions SUV0, SAFIR, and Planet Imager. Membrane transfer technology at JPL provides a rich technical resource for optical quality surface figure for a wide range of deformable mirrors with apertures up to 250 mm [10]. Meeting all ELT AO requirements (Table I) clearly will be very challenging.

CfAO MEMS PLAN FOR YEAR FOUR (2002/2003) AND BEYOND

All direct CfAO funding for MEMS in year four is devoted to developing MEMS devices suitable for application to vision science instrumentation; in particular, this application requires high-stroke devices (goal of 10 microns). Four projects are currently approved for funding: BMC, BSAC, IRIS AO, and Lucent. Boston Micromachines has a modified actuator design using the Cronos fabrication process that increases actuator stroke to ~ 4 microns, and increases format to 256 actuators. Iris AO, the BSAC spin-off, will develop integrated mirrors having approximately 50 actuators with tip-tilt and piston motion, 6 microns actuator range, a 3 mm clear aperture, and unit cost of approximately \$25k. They plan to extend actuator range to greater than 10 microns with greater than 100 Hz operating frequency. The Berkeley Sensor & Actuator Center will transfer demonstrated actuator fabrication capabilities to a low temperature SiGe process to enable integrated CMOS electronics, which will lower the unit cost. Lucent will develop mirrors meeting the vision science goals using the electret membrane technology. Other MEMS DM efforts are being monitored for possible vision science application, including Stanford University spin-off Intellite, Stanford, the Fraunhofer Institute [11], Boston University metal mirror with integrated electronics [12], the University of Colorado [13], and JPL [8, 9, 10]. In year five, the CfAO will strive to refine the MEMS DMs to meet vision science goals, particularly increasing actuator range and integrating electronics for reduced unit cost and form factor.

In year four, LLNL and Boston Micromachines will assess extension of the 1000 actuator BMC DM to ~ 4000 actuators to meet ExAO device specifications. This goal is expected to be consistent with Phase II of the DARPA CCIT program. Methods for increasing actuator range to five microns, and improving surface quality, fill factor, and reflectivity (possibly using silver with an overcoating) also will be evaluated. As with the Vision Science theme, other MEMS DM efforts are being monitored for possible ExAO application, including Intellite, Stanford, Boston University, Lucent,

BSAC, the Fraunhofer Institute, and JPL. In year five, the CfAO will issue a request for proposals for the ExAO DM, contingent on a successful ExAO program preliminary design review.

The CfAO, in cooperation with ELT construction projects, will help assess technologies and consider proposals to address key ELT AO challenges for MEMS DMs in year four, particularly clear aperture requirements. Deformable mirrors for Extremely Large Telescopes must be relatively large by MEMS standards (~300 mm clear aperture). The CfAO is monitoring MEMS development activities funded by other sources (DARPA, NRO, NASA), to determine whether MEMS are a feasible approach for this application which might warrant further research.

SUMMARY

The Center for Adaptive Optics is sponsoring, planning, and coordinating research on MEMS deformable mirrors for three application areas: vision science, extreme adaptive optics for discovery of extrasolar planets, and adaptive optics for extremely large telescopes. These applications have different specifications for the MEMS devices, and as a result, different design and fabrication approaches are being pursued. Now beginning its fourth year, the CfAO MEMS development cycle is on schedule, with the demonstration of 1024 element devices. Devices targeted for specific applications with increased integration are planned for development this year.

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