Adaptive optic correction using microelectromechanical deformable mirrors

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Abstract. A micromachined deformable mirror (μ-DM) for optical wavefront correction is described. Design and manufacturing approaches for μ-DMs are detailed. The μ-DM employs a flexible silicon membrane supported by mechanical attachments to an array of electrostatic parallel plate actuators. Devices are fabricated through surface micromachining using polycrystalline silicon thin films. μ-DM membranes measuring 2 mm$\times$2 mm$\times$2 μm, supported by 100 actuators are described. Figures of merit include stroke of 2 μm, resolution of 10 nm, and frequency bandwidth dc to 7 kHz in air. The devices are compact, inexpensive to fabricate, exhibit no hysteresis, and use only a small fraction of the power required for conventional DMs. Performance of an adaptive optics system using a μ-DM is characterized in a closed-loop control experiment. Significant reduction in quasistatic wavefront phase error is achieved. Advantages and limitations of μ-DMs are described in relation to conventional adaptive optics systems and to emerging applications of adaptive optics such as high-resolution correction, small-aperture systems, and optical communication. [DOI: 10.1117/1.1447230]

Subject terms: adaptive optics; actuators; aberrations; micromachined; mirrors; optical phase correction; wavefront reconstruction.

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1 Introduction

Adaptive optics (AO) is the control of optical wavefront phase in a real-time, closed-loop fashion.[1] A typical AO system is a combination of a deformable mirror (DM), a wavefront sensor, and a real-time controller, which is used to modulate the spatial phase of the optical wavefront, as shown in Fig. 1.

The principles of resolution enhancement by AO have been established for several decades and have been applied successfully to a number of large-aperture ground-based telescope systems where the large cost of deformable mirror systems is not prohibitive. Put simply, adaptive optics is a way of improving optical resolution by compensating for fabrication errors (e.g., misshapen or thermally deformed mirrors) or optical path aberrations (e.g., turbulent atmosphere effects). Such a system requires that a compensating mirror be deformed in such a way that unwanted aberrations are measured and then canceled (usually through a process called phase conjugation). In many visible imaging applications, system requirements include nanometer-scale precision, several micrometers of stroke, hundreds of hertz bandwidth, and tens to hundreds of actuators to achieve diffraction-limited performance.

The primary variables of interest in an AO system are the number of actuators in the DM, the motion resolution of each pixel, the control bandwidth of each actuator, and the maximum available actuator stroke.[2] Design goals for the DM system were determined based on the electromechanical performance of a commercial macroscopic DM used for adaptive astronomical telescope imaging systems. To meet these design specifications, surface micromachined microelectromechanical deformable mirrors were developed with 100 electrostatic actuators, 2-μm stroke per actuator, 10-nm resolution, 1-kHz open-loop bandwidth, and 1-cm^2 total active mirror area,[3–5] as is described in Table 1.

The Boston University (BU) micromachined DMs (μ-DMs) consists of 10$\times$10 arrays of electrostatic actuators supporting a thin-film continuous or semicontinuous silicon mirror membrane via attachment posts. Cuts were introduced into the mirror surface to reduce inherent stress in the mirror surface while maintaining a fill factor of 98.6%. The actuators consist of a 300-μm$\times$300-μm$\times$3-μm polycrystalline silicon membrane anchored to a substrate on two opposing sides. Each actuator membrane is supported over an isolated polycrystalline address electrode. Cross-sectional schematics of two types of μ-DM are depicted in Fig. 2.

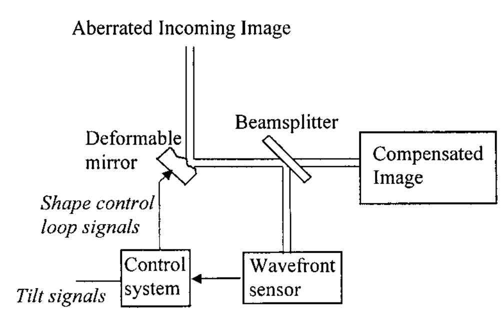

Fig. 1 Elements of a simple adaptive-optical imaging system.

Table 1

Specification	BU μ-DM
Number of actuators	100
Actuation	Integrated electrostatic
Package size	10 cm^3
Power consumption	0.2 W/channel
Actuator spacing	0.3 mm
Actuator stroke	2 μm
Actuator repeatability	10 nm
Hysteresis	0%
Surface roughness, Rq	50 nm (root mean square)
Bandwidth in air	7 kHz
Maximum deflection	1.9 μm at 241 V

In surface micromachining fabrication, optically flat mirrors are difficult to achieve due to residual stress gradients resulting from high-temperature thin film deposition processes. Such stress gradients cause out-of-plane bending of thin film structures on their release from sacrificial layers. A detailed analysis of stress-induced deformation for these mirrors as well as novel approaches to measurement and modification of mirror stress after structural release will be presented elsewhere.

Two types of continuous phase mirrors were designed. The first is a continuous membrane mirror with a fill factor of 99.7%. The continuous mirror device employs a single mirror membrane supported by multiple post attachments to an actuator array, as shown schematically in Fig. 2(a). The second is a continuous membrane mirror with interpost cuts introduced into the mirror surface in order to relieve stress in the mirror membrane. It has a fill factor of 98.6%. This stress-relieved design divides the mirror membrane into segments that are supported at their corners by post attachments to the underlying actuators. Post attachments are shared among adjacent mirror segments to ensure optical phase continuity from segment to segment. Mirror and actuator thicknesses in the custom fabrication of the current mirrors were chosen on the basis of previous experimental and analytical work with smaller mirror and actuator arrays.[5]

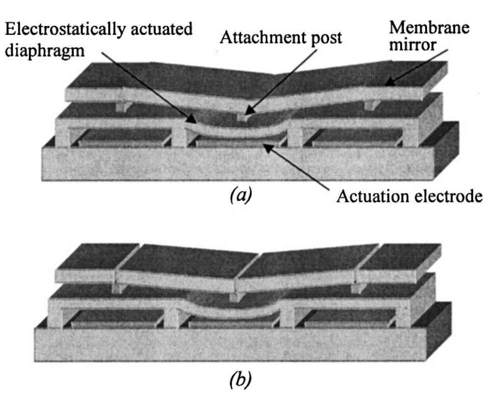

Fig. 2 Schematic of DM array sections with (a) continuous mirrors and (b) stress-relieved mirrors.

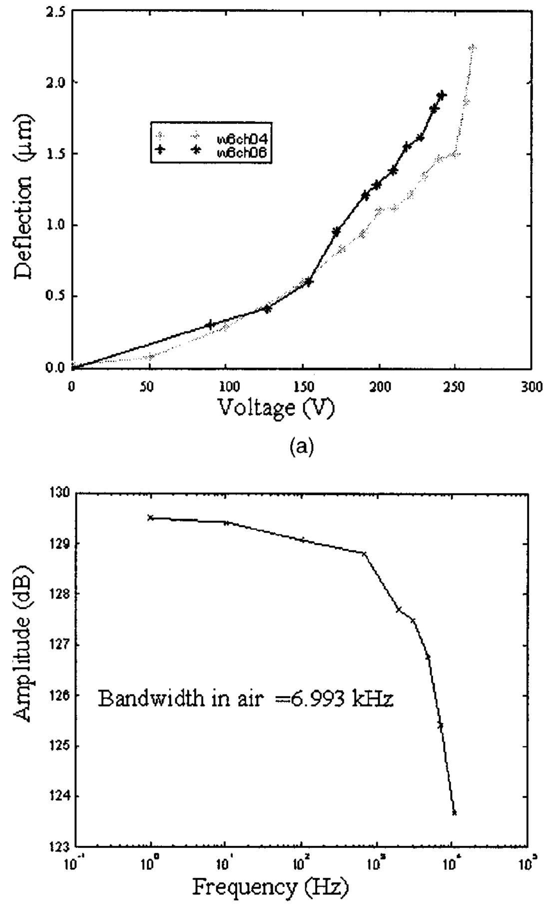

Fig. 3 (a) Voltage deflection curves and (b) frequency response in air for a 10×10 250-μm mirror.

The deflection of each actuator is a monotonically increasing function of applied voltage and is used to control the shape of the continuous and stress-relieved mirrors. A continuous mirror has the advantage that it does not introduce as much diffraction in the reflected beam as the stress-relieved mirrors, since the latter employs a regularly spaced array of cuts in the mirror surface. The stress-relieved mirror maintains phase continuity but introduces unwanted diffraction and a small ($\sim$1%) loss in fill factor. The mirror influence function, defined as the ratio of deflection above an unenergized actuator to that of an energized neighbor is 30% for a continuous mirror and 11% for a stress-relieved mirror. The influence function is important to maintain continuous phase slope as well as continuous phase, which enables the mirror to form the proper shapes to correct a distorted wavefront. In a typical astronomical AO mirror, an influence function of 10% has been empirically determined as a standard for good mirror performance. BU microelectromechanical system (MEMS) DMs were designed to have approximately a 10% influence function following the empirical standard used in astronomical AO. The mirror design can be easily adjusted to alter the influence function. A thicker mirror membrane will be much stiffer and hence the influence function and the mirror flatness will be greater. The same increase in influence function can be achieved by thinning the actuator membrane, which affects

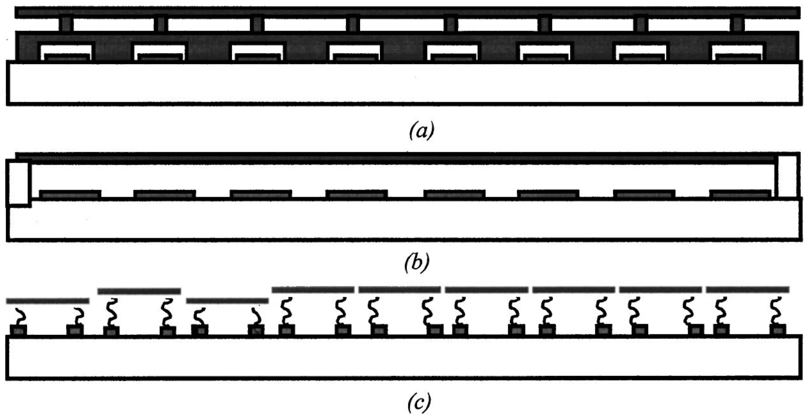

Fig. 4 (a) BU continuous mirror system, (b) Delft University continuous mirror for spatial light modulation, and (c) AFIT segmented mirror array.

the restoring force of the actuator beam and hence its actuation voltage.

Actuator and mirror design are constrained by optical, electrical, and mechanical trade-offs and manufacturing process limitations. For example, smaller actuators can be packed more closely together, reducing the effect of stress induced curvature. However, a smaller actuator requires larger actuation voltage to achieve a given displacement stroke. If the actuator is made too small, full stroke cannot be achieved before dielectric breakdown of the air in the actuator gap. In Fig. 3(a), the voltage versus deflection curves measured for two different mirrors supported on 250-μm square actuators are plotted. In Fig. 3(b), the measured bandwidth of one of these actuators is shown to be 7 kHz. The tip-tilt 10×10 actuator array μ-DM was developed at BU and incorporated into an adaptive optics setup for phase modulation. Actuation of a 200-μm actuator with 300 V provides approximately 1.5 μm of deflection, in a monotonic reproducible manner, with no hysteresis. The frequency response roll off at 7 kHz is primarily due to air damping.

Deformable mirror bandwidth is important for AO because the time scale for aberration fluctuations is on the order of a few milliseconds. Ideally, the mirror response should be fast enough so that it does not contribute to the latency of the control system. Mirror shape should be controlled at a speed faster than that of the changing aberration.[4]

Other researchers have fabricated μ-DM systems using both bulk micromachining and surface micromachining techniques. The most advanced is a bulk micromachined, freely suspended, continuous surface adaptive mirror, developed by Delft University and commercially available through OKO Technologies, which has been implemented as a spatial light modulator. This circular 12-mm mirror is made of a 0.5-μm-thick silicon nitride membrane coated with Al and suspended across a rectangular window. A 37-electrode pattern was used to electrostatically control the shape of the reflecting surface.[6] This mirror is limited by its varifocal nature. Since the surface is always monotonically decreasing, some type of spherical compensating optics must be used to produce a resultant flat wavefront. Another deformable mirror system has been developed at the Air Force Institute of Technology[7] (AFIT). It consists of a hexagonal array of 127 segmented mirrors fabricated by surface micromachining. This deformable mirror has been used for static correction of a quadratic optical aberration

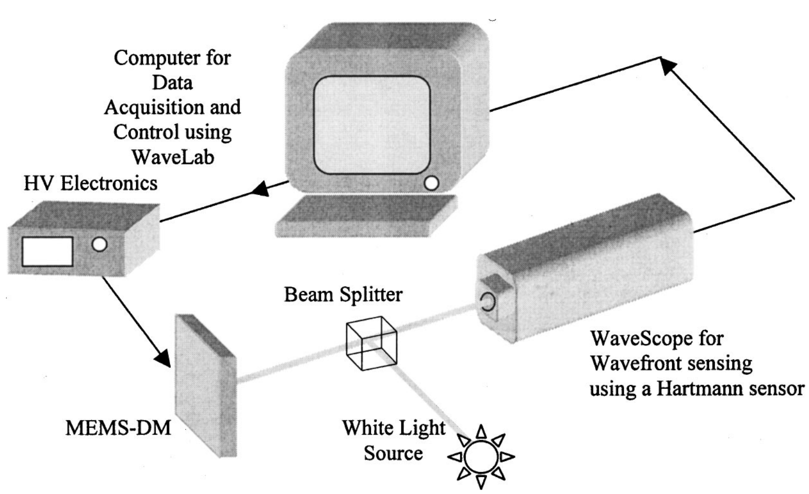

Fig. 5 Depiction of the AO setup.

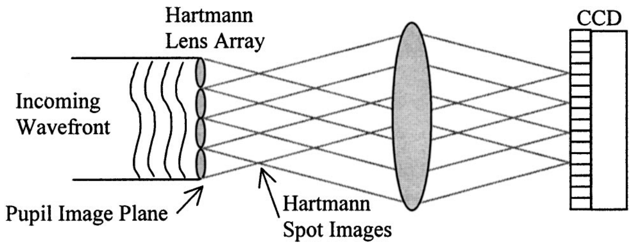

Fig. 6 Hartmann sensor array with incoming wavefront.

with some improvement in Strehl ratio.* A schematic side view of all three mirror systems is shown in Fig. 4.

2 Adaptive Optics Using the Wavescope Wavefront Sensor Data Analysis System

The experimental setup included an automated Shack-Hartmann sensor (WaveScope wavefront measurement system manufactured by Adaptive Optics Associates), a white light source, and high-voltage electronics to drive the MEMS-DM, as shown in Fig. 5.

The software in the WaveScope System is extended to control the voltage used to drive the MEMS device and to make quasi-real-time closed-loop wavefront control. One of the most challenging aspects of correcting an incoming aberration is to create a conjugate shape on the mirror. To characterize and calibrate the μ-DM performance, each actuator was energized independently to 280 V, and the resulting change in wavefront shape was measured using the Shack Hartmann sensor. This information was then used to create modal poke reconstructors that would allow the generation of correction signals to be sent to the DM actuator array.[8]

3 AO Experiment

A white light source and WaveScope, a Shack Hartmann-style wavefront sensor, were used to measure the deformations in the mirror surface. At the heart of the Shack Hartmann sensor is a square array of lenslets. When illuminated with a planar wavefront, the Shack Hartmann sensor will create a pattern of spots in the focal plane. Any aberration in the wavefront will create an x-y displacement in each spot, which correlates to the local wavefront slope. Local slope in the incident wavefront will displace the focal plane spot of the corresponding lenslet, which is detected with a CCD camera, as shown in Fig. 6.

Spot displacements are then used to reconstruct the wavefront phase to within a constant. A photograph of the experimental setup is shown in Fig. 7.

A circular aperture with a diameter of 1.82 mm on the deformable mirror was used to view an inner area of five mirror segments. The initial mirror figure was measured to have a peak-to-valley depth of 35.9 nm and a root mean square (rms) value of 4.4 nm, as shown in the optical path difference (OPD) measurement of Fig. 8(a). The values are measured relative to a section of the silicon substrate. A

*Strehl ratio S, is a common measure of imaging performance. It is the ratio of on-axis intensity of an aberrated image to on-axis intensity of the unaberrated image.

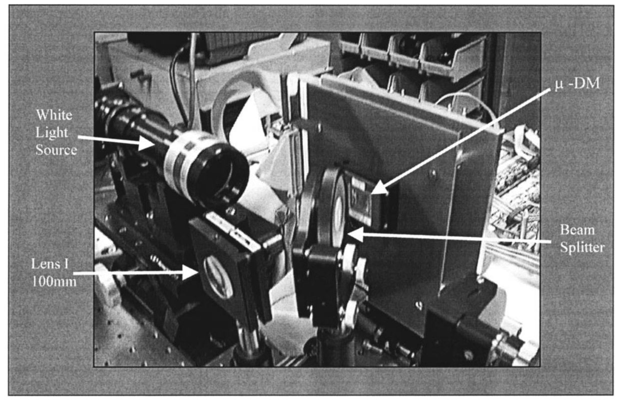

Fig. 7 Photograph of the experimental AO setup.

static aberration was introduced into the beam path to create a peak-to-valley distortion of 521 nm and an rms value of 574 nm, as shown in the OPD measurement of Fig. 8(b).

A linear proportional controller with a bandwidth of approximately 2 Hz was implemented to compensate for wavefront error introduced by quasistatic aberrations. Closed-loop voltage signals, or drive signals, were generated by the WaveScope and sent to the high-voltage electronics to control each actuator. Wavefront error has been reduced by a factor of 7. As shown in Fig. 9 and Table 2, the controller reduced the aberration introduced in the beam path by a significant amount.

A steady state was reached after about 21 iterations of the control algorithm. The residual error in the wavefront was decomposed mathematically into a best-fit series of Zernike polynomials. Coefficients for the first eight terms of this decomposition are enumerated in Table 3, both before and after compensation.

Another method of measuring the performance of an AO system is to measure its point spread function (PSF). The on-axis peak of the PSF, called the Strehl ratio S, is a common measure of imaging performance.[9] A Strehl ratio of 1 would be considered perfect. The aberration image had a Strehl ratio of $S=0.0034$, while the corrected wavefront had a Strehl ratio of $S=0.1950$.

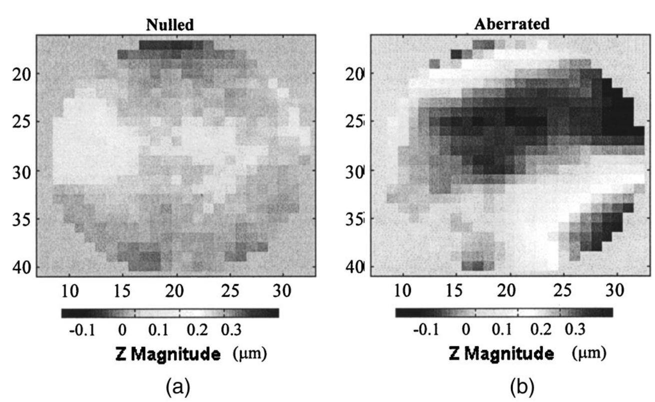

Fig. 8 Measurement of mirror surface with (a) no aberration and (b) introduced aberration.

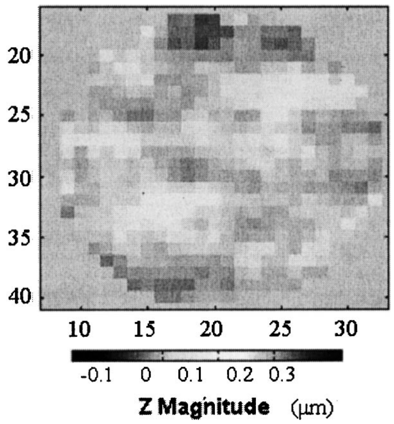

Fig. 9 Measurement of mirror surface during closed-loop control.

Table 3 Coefficient for the terms of decomposition.

	Mode of Aberration	Zernike Equation	Aberrated Wavefront (nm)	Corrected Wavefront (nm)
1	X tilt	$r\cos(t)$	61	0
2	Y tilt	$r\sin(t)$	27	4
3	Focus	$2r^2-1$	73	0
4	0 astigmatism	$2r^2\cos(2t)$	67	16
5	45 astigmatism	$2r^2\sin(2t)$	146	−2
6	X coma	$(3r^2-2)r\cos(t)$	−68	2
7	Y coma	$(3r^2-2)r\sin(t)$	−30	−3
8	Spherical	$6r^4-6r^2+1$	−2	0

4 Results

Results of the closed-loop AO compensation show that there is a reduction in the wavefront error. However, improvements are referenced to a flattened mirror with low optical quality. The relatively poor optical quality is due to low reflectivity as well as contour error in the mirror membrane. Mirror reflectivity without a highly reflective coating is of the order of 40%. Stress in the mirror membrane from fabrication process results in a contour error that introduces error in the incident wavefront. Reliability and yield in this fabrication run were low due to process development experiments conducted during fabrication. A new fabrication run with optimized mirror design was subsequently completed, yielding significant improvement in mirror quality and consequently in AO performance.

5 Conclusion

The goal of this research was to show the feasibility of using a MEMS-DM for phase modulation in an AO system. A significant reduction in wavefront phase error was achieved, even with 1 μm of deflection. The next generation of devices currently under development at BU are capable of achieving 2 μm of deflection and will be able to correct more than the current set of MEMS-DMs reported in this paper. Nevertheless, the performance exhibited by these prototype MEMS-DMs is promising. Improvements in the design currently being fabricated have been made to improve optical quality, reflectivity, and surface planarity by reducing the surface topography from the actuator thin films.

Table 2

Mirror Surface	Peak-to-Valley Flatness Error (μm)	rms Flatness Error (μm)
Nulled wavefront	0.04	0.004
Aberrated wavefront	0.52	0.057
Corrected wavefront	0.10	0.008

Acknowledgments

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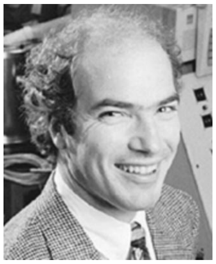

Thomas G. Bifano has more than a decade of research experience in the field of precision optical engineering. His principal areas of expertise concern measurement, actuation, and fabrication at the submicrometer tolerance level in optical applications. He received his BS and MS degrees in mechanical engineering and materials science from Duke University in 1980 and 1983, respectively, and his PhD in mechanical engineering from the NC State University in 1988. He has organized and chaired two international conferences for the American Society for Precision Engineering and recently served as a member of the board of directors for that society. Dr. Bifano joined the College of Engineering at Boston University (BU) in 1988, where he now chairs the Manufacturing Engineering Department. He directs the Precision Optics Laboratory at the BU Photonics Center. His research at BU currently includes the development of micromechanical mirror arrays on a silicon chip, the development of new precision manufacturing technology for compact disk production, and basic research on the design, fabrication, and control of new classes of smart materials.

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