Use of a microelectromechanical mirror for adaptive optics in the human eye

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Ophthalmic instrumentation equipped with adaptive optics offers the possibility of rapid and automated correction of the eye's optics for improving vision and for improving images of the retina. One factor that limits the widespread implementation of adaptive optics is the cost of the wave-front corrector, such as a deformable mirror. In addition, the large apertures of these elements require high pupil magnification, and hence the systems tend to be physically large. We present what are believed to be the first closed-loop results when a compact, low-cost, surface micromachined, microelectromechanical mirror is used in a vision adaptive-optics system. The correction performance of the mirror is shown to be comparable to that of a Xinetics mirror for a 4.6-mm pupil size. Furthermore, for a pupil diameter of 6.0-mm, the residual rms error is reduced from 0.36 to 0.12 μm and individual photoreceptors are resolved at a pupil eccentricity of 1° from the fovea.

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Several authors have demonstrated the use of adaptive optics (AO) for the correction of ocular wave-front aberrations. Dreher *et al.*[1] were the first to use a deformable mirror (DM) to ameliorate the eye's astigmatism. Liang *et al.*[2] combined a DM with a Hartmann–Shack wave-front sensor and demonstrated the first active correction of higher-order aberrations. Their systems used conventional lead magnesium niobate or lead zirconate titanate DMs commonly found in astronomical AO systems. These mirrors are expensive, roughly $1,000 per channel (with 97 or more channels needed to correct the eye's aberrations). They have large apertures (4–8 cm), which implies that long optical paths are needed for the required pupil magnification. In addition, these mirrors lack the required amount of corrective range, which is sufficient for astronomy but not for vision.

To lower the cost of ophthalmic AO systems, researchers have explored several different mirror technologies. Vargas-Martin *et al.*[3] used a transmissive liquid-crystal spatial light modulator as their corrective element. The device had a pixelated design that limited its spatial resolution and was driven in an open-loop mode. A solution to these obstacles is to phase wrap an optically addressed liquid-crystal spatial light modulator to extend its corrective range. Such devices have extremely high spatial resolution (480×480 pixels) and an adequate temporal response for vision. However, they cannot be used in broadband illumination and also need polarized light.

Bulk micromachined membrane deformable mirrors[4] have been used to correct the dynamic changes in the human eye up to 21 Zernike modes.[5] However, these mirrors suffer from the fact that their available stroke decreases as higher-order modes are corrected. For example, for low-order modes, one can typically get 1.2 μm of mirror deflection; as the order is increased this falls to 0.7 μm. Recent advances in micromachining technology led to many integrated and extremely small devices that have found uses mainly in the telecommunications field, e.g., in optical switches and cross connects. Texas Instruments has created a digital micromirror device that comprises up to 1×10^6 mirror segments. Such chips have found use in high-quality projection systems, although their bistable nature precludes their use as a DM for vision AO.

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Presented here are the results of using a surface micromachined, microelectromechanical (MEMS) mirror. A major advantage of these mirrors is that they utilize well-established integrated circuit fabrication processes. With existing technology, these mirrors promise low cost and high reliability. The number of actuators can be easily scaled to give sufficient spatial resolution while retaining a small overall mirror diameter.

The current Rochester AO system (see Fig. 1), described in more detail elsewhere,[6] served as a testbed for the MEMS device. For the results presented here, the MEMS subsystem was mounted on a separate breadboard, which could be inserted via kinematic bases. The subsystem consisted of a pair of relay mirrors and achromatic collimating lenses. This facilitated switching between the MEMS and Xinetics DM, and they could then be directly compared. Typically, a subject was tested with the MEMS mirror, the breadboard was subsequently removed, and the same experiments were performed immediately afterward with the Xinetics DM.

The MEMS mirror described elsewhere[7] was designed by Boston Micromachines (BMC)–University of Boston. For this experiment a piecewise continuous mirror was used. To improve the longevity of the device, the drive voltage was reduced from 220 to 160 V, yielding a mirror stroke of 1.4 μm. A comparison of the MEMS and Xinetics DMs is given in Table 1.

In the first experiment, a 4.6-mm pupil was used, corresponding to a 37-actuator subset on both the Xinetics and the MEMS mirrors. The beam diameter on the MEMS is controlled by the focal length of the collimating lens; a 50-mm focal length gives a beam diameter of 1.9 mm. The reason for choosing this pupil size was that few subjects have ocular aberrations less than the range of the (present) MEMS mirror for larger pupil sizes. At 4.6 mm, most subjects have a peak-to-valley error less than the $\sim$2.8-μm wave-front range of the mirror. This pupil size is then sampled by 89 lenslets in the Hartmann–Shack wave-front sensor plane, allowing for the accurate reconstruction of 30 Zernike terms.

Four subjects were tested, and any defocus was corrected by movement of the bite-bar mount. For subjects GYY and HH, a trial lens was added to correct their astigmatism. None of the subjects' pupils was dilated or accommodation paralyzed. Figure 2 shows the pupil rms and Strehl ratio values before and after the AO loop is closed with the MEMS and Xinetics mirrors, respectively. As can be observed, all subjects were corrected to $\sim$0.10 μm rms, and the MEMS performed as well as the Xinetics mirror. The correction was achieved in five frames, which equals a time period of $\sim$0.35 s. As an additional check, the open- and closed-loop temporal power spectra were measured for each device. The disturbance rejection curves for each mirror were in good agreement with each other, giving a closed-loop bandwidth of 0.8 Hz, as expected.[6]

Most of the fitting error is due to edge effects, where the surrounding actuators influence the correction. The mirror was initially biased to its midrange and the outer actuators held at this value. Another difference is that the influence functions are not the same; the Xinetics mirror has a Gaussian-like profile, whereas the BMC MEMS mirror has a pyramidal shape. Although controlling both by use of the direct slope method is still valid, there is a difference in the fitting error.

In the next experiment the same 37-actuator subset of the MEMS mirror was used to correct a larger pupil. The collimating optics were changed to demagnify the pupil further. Typically, for retinal imaging a

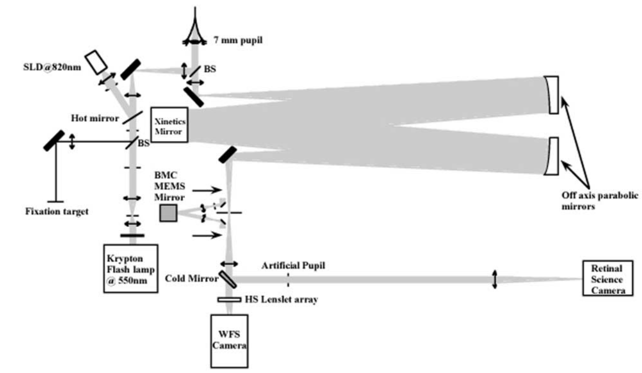

Fig. 1. Rochester AO system incorporating a BMC MEMS breadboard. 50-mm focal-length collimating lenses were used to obtain an incident half-angle onto the MEMS mirror of 15° with a beam diameter of 2.8 mm. SLD, superluminescent diode; BSs, beam splitters; HS, Hartmann–Shack; WFS, wave-front sensor.

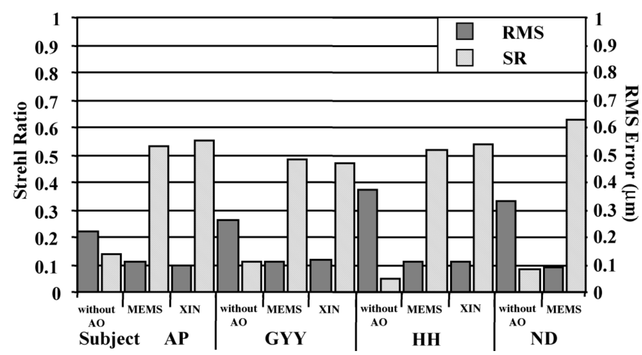

Fig. 2. Results of correcting a 4.6-mm pupil for four subjects, AP, GYY, HH, and ND, each over 10 trials. Xinetics mirror (XIN) results were not obtained for subject ND. All experimental conditions were the same in each case.

Table 1. Comparison of the Xinetics DM and the BMC MEMS Mirror

Specification	Mirror	
	Xinetics	BMC MEMS
Active area (mm)	$\phi = 75$	3.3×3.3
No. of actuators	97	12×12
Surface type	Continuous	Piecewise
Stroke (wave front)	± 4 μm	± 2 μm
Response speed	4 kHz	3.5 kHz
Operating voltage	100 V	220 V
Cost (per actuator)	\$1,000	$\sim$\$10[a]
Availability	Commercial	Prototype

[a]Projected cost with an integrated driver CMOS.

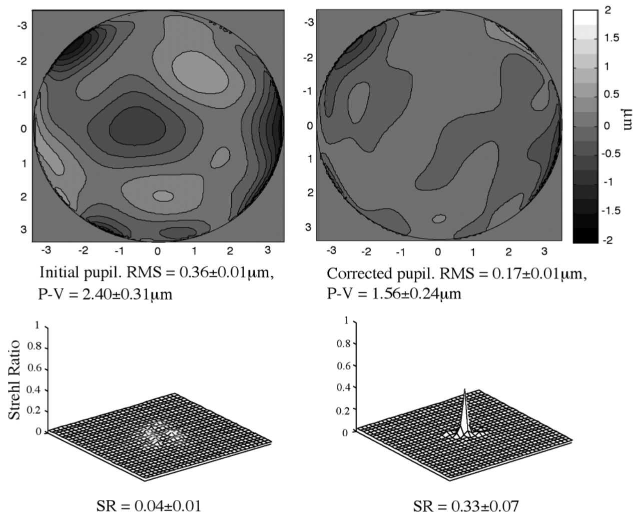

Fig. 3. Before and after AO correction with the BMC MEMS mirror for a 6.8-mm pupil. Defocus was corrected before both measurements. An average of 10 trials was used. P-V, peak to valley.

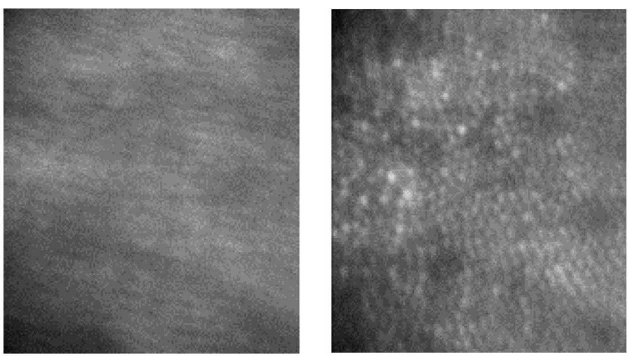

Fig. 4. Images of the human retina at an eccentricity of 1° before (left) and after (right) AO correction. Photoreceptors are clearly visible in the corrected image. Each result is a registered sum of six images. The field of view is 0.3°, corresponding to 75 μm on the retina (horizontal dimension).

6.8-mm pupil is corrected, and the central 6-mm pupil is used for retinal imaging. This eliminates any edge effects that might be present. On correction of the wave aberration, a krypton flash lamp is triggered either after a preset number of frames or after reaching a desired rms value. Figure 3 shows the initial 6.8-mm pupil profile and corresponding point-spread function for subject AP (peak to valley, 2.40 μm). As can be observed, the rms decreases, along with an eightfold increase in the value of the Strehl ratio. There was an actuator located at the top left of the pupil that did not always respond to driver signals; hence the poor correction in this area. On truncation of the pupil to 6 mm (5×5 mirror actuators), the rms decreases to 0.12 ± 0.01 μm (peak to valley, 0.85 ± 0.09 μm), and the Strehl ratio increases to 0.45 ± 0.09. Figure 4 shows retinal mosaic images before and after correction, taken at 1° eccentricity for subject AP. Both images are a registered sum of six images, and the field of view is 0.25°, corresponding to 75 μm on the retina. On examining the image power spectra, we found that there was a fourfold increase in the relative power at the cone spatial frequency.

To our knowledge, this is the first time that photoreceptors have been resolved *in vivo* with an AO system that utilizes a mirror other than a Xinetics DM. The results show great promise that a MEMS device will be suitable in a commercial ophthalmic instrument equipped with AO. Other mirror designs[8,9] in development offer the possibility of very high stroke MEMS devices that will be sufficient for vision AO at large pupil sizes. Future work on incorporating the driver electronics into underlying complementary metal-oxide semiconductor circuitry will increase their applicability even more. Other research groups are developing fully integrated Hartmann sensors[10] that may be applicable to vision. One can imagine vision AO systems in which the two principal components, the DM and wave-front sensor, are fabricated by use of inexpensive, existing integrated circuit manufacturing.

In conclusion, we have demonstrated the feasibility of using a compact, low-cost MEMS mirror in an AO system for the human eye and have shown that the achievable correction is comparable to that with a conventional Xinetics DM.

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References

1. A. W. Dreher, J. F. Bille, and R. N. Weinreb, Appl. Opt. **28,** 804 (1989).
2. J. Liang, D. R. Williams, and D. T. Miller, J. Opt. Soc. Am. A **14,** 2884 (1997).
3. F. Vargas-Martin, P. M. Prieto, and P. Artal, J. Opt. Soc. Am. A **15,** 2552 (1998).
4. G. V. Vdovin and P. M. Sarro, Appl. Opt. **34,** 2968 (1995).
5. E. J. Fernandez, I. Iglesias, and P. Artal, Opt. Lett. **26,** 746 (2001).
6. H. Hofer, L. Chen, G. Y. Yoon, B. Singer, Y. Yamauchi, and D. R. Williams, Opt. Express **8,** 631 (2001), www.opticsexpress.org.
7. T. G. Bifano, J. Perreault, R. Krishnamoorthy-Mali, and M. N. Horenstein, IEEE J. Sel. Top. Quantum Electron. **5,** 83 (1999).
8. M. A. Helmbrecht, U. Srinivasan, C. Rembe, R. T. Howe, and R. S. Muller, in *Proceedings of the 11th International Conference on Solid State Sensors and Actuators* (Springer, New York, 2001), pp. 1290–1293.
9. P. Kurczynski, A. J. Tyson, B. Sadoulet, D. J. Bishop, and D. R. Williams, Proc. SPIE **4561,** 147 (2001).
10. D. W. de Lima Montiero, G. Vdovin, and M. Loktev, presented at the 3rd International Conference on the Use of AO for Industry and Medicine, Albuquerque, N.M., July 23–26, 2001.