

The Application of MEMS Technology for Adaptive Optics in Vision Science

Nathan Doble and David R. Williams

Abstract—Recent years have seen remarkable results in high-resolution imaging and testing of the human visual system. The ability to obtain *in vivo* images of the human fundus on the micrometer scale will allow for much earlier diagnosis and treatment of a range of retina diseases. These advances have been made possible in part through the use of adaptive optics (AO). In order to utilize the full numerical aperture and, hence, maximize the resolution of the eye, it is necessary to provide a means of correcting all of the ocular aberrations. The concept of AO has been used successfully to overcome this difficulty. A key component of such a system is an optical element that can be deformed to provide high-order correction of these aberrations. Existing AO systems make use of deformable mirrors that were developed for large ground-based telescopes. In a drive to reduce their size and cost, fabrication of this element using microelectromechanical systems (MEMS) has been actively pursued. This paper explains the challenges in high-resolution imaging of the human eye and details how MEMS technology has been used to further research in this area.

Index Terms—Adaptive optics (AO), deformable mirror (DM), microelectromechanical devices, micromachining, optical aberrations, optical imaging, optics.

I. INTRODUCTION

THE human eye is a complex optical instrument whose performance is compromised by the aberrations present. These aberrations limit one's visual perception when viewing the world—hence, the need for spectacles and contact lenses. Conversely, they also limit the ability for high resolution when the eye's optics are used in reverse for *in vivo* imaging of the retina. Spectacles or contact lenses, for instance, only provide a low-order, static correction of these aberrations, namely, defocus and astigmatism. Adaptive optics (AO) is a technique that can correct these aberrations and also higher order terms that vary both spatially and temporally in real time. This has the effect of improving greatly the quality of retinal images obtained with several different imaging modalities. In addition, this aberration correction essentially bypasses any effect of the eye's aberrations and allows the limits of human vision to be explored at the neural level.

The basic concept of AO is shown in Fig. 1 and was first proposed by the astronomer Babcock [1] in 1953. His concept of

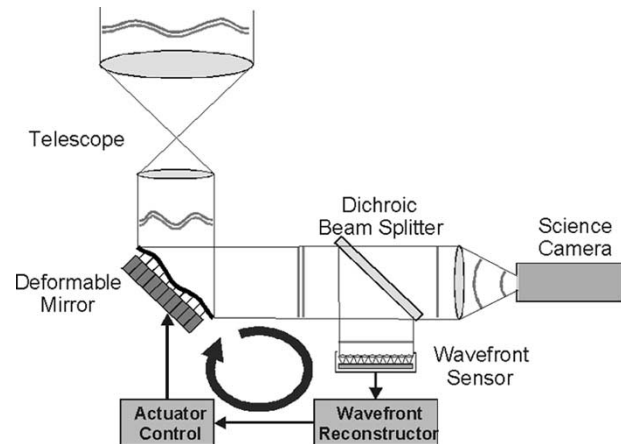


Fig. 1. Basic principle of an AO system. The aberrated light—in this case, from a telescope—is reflected off the DM. A small fraction of the light is split to the WFS and the appropriate voltage commands determined by the control computers and fed back to the DM. This continual measurement and correction is termed closed loop. The majority of the light is used in forming the image at the science camera. Courtesy of M. Helmbrecht, Iris AO, Inc., Berkeley, CA.

AO was required to remove the deleterious aberrations introduced by the earth's atmosphere when using large ground-based telescopes. Due to technological problems, Babcock's idea was not implemented at that time. For astronomy, the distortion is provided by the earth's atmosphere, but any application where there is an intervening source of aberration can benefit from AO.

The application of AO can be broken down into three main subsystems.

- **The Wavefront Sensor (WFS)**—This measures the optical aberrations in the incoming wavefront. This can take many forms, e.g., interferometry, slope, or wavefront curvature measurement.
- **The Control Computer**—This takes the output of the WFS and converts it to voltage commands that are sent to the deformable mirror (DM).
- **The DM**—This provides the conjugate correction to the optical distortions. Many forms exist: conventional piezoelectric, bimorph, liquid crystal, and microelectromechanical systems (MEMS).

This continual process of measurement and correction of the aberration is termed closed loop. From the 10-m aperture of the giant Keck [2] telescope to the 7-mm aperture of the eye, AO is finding its way into many diverse fields [3]–[5], in addition to vision science and astronomy. To facilitate the implementation of AO, there has been interest in the use of MEMS to improve these systems' capabilities. This paper deals with the application of MEMS to vision science AO. Section II details the structure of the eye and the need for AO.

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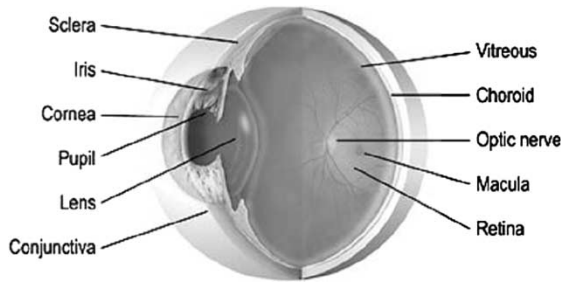


Fig. 2. The structure of the eye; the main sources of optical aberration are the cornea and lens. The retinal surface contains millions of photoreceptors, which give us our visual perception and the appearance of color. The photoreceptors are a few micrometers in diameter and are unresolvable without the application of AO.

II. THE STRUCTURE OF THE EYE AND THE NEED FOR AO

One of the most interesting and publicized applications of AO has been in vision science and the imaging of the retina. Fig. 2 shows a cross section through the human eye and shows the main sources of aberration, namely, the cornea and lens. These elements introduce high-order spatial aberrations [6], which along with temporal instabilities limit the ability to obtain high-resolution images of retinal cells. Theoretically, the resolution of the eye can be calculated from (1)

$$r \approx 1.22f \frac{\lambda}{D} \quad (1)$$

where r is the radius of the focused spot, f is the focal length of the eye, λ is the imaging wavelength, and D is the pupil diameter.

Hence, the best resolution would be achieved using the shortest wavelength λ and the largest possible aperture D (the focal length being fixed). For the human eye, with $D = 7$ mm, $f = 17$ mm, and imaging at $\lambda = 550$ nm, one could theoretically achieve spot sizes on the order of $2\text{--}3 \mu\text{m}$. In practice, the transverse resolution is limited by aberrations to $5 \mu\text{m}$. In order to increase the resolution, it is relatively straightforward to change the imaging wavelength (one is limited only by the transmission properties of the ocular media). However, using the largest pupil diameter results in an increase in the ocular aberrations which completely dominate the potential benefit in resolution. For humans in normal daylight conditions, the pupil is around $2\text{--}3$ mm in diameter; hence, their effect is small. With larger pupils, the impact of aberrations on optical quality is considerable. By taking the subject's aberration data from a standard ocular WFS, it is possible to visualize the effect of aberrations on retinal image quality. The squared modulus of the Fourier transform gives the point spread function (PSF). By truncating the measured wavefront profile and recalculating the PSF, it is possible to simulate the perceived image quality for different pupil diameters. Fig. 3 shows the PSF for a typical human eye as the pupil diameter increases. The PSF is essentially the image of a point source propagated through an optical system, in this case the eye. A PSF with a small, well-defined central core implies better system resolution. As can be seen, the PSF degrades dramatically with increased pupil size. In the same way that large pupils limit subjective visual perception, this increased aberration also means reduced beam

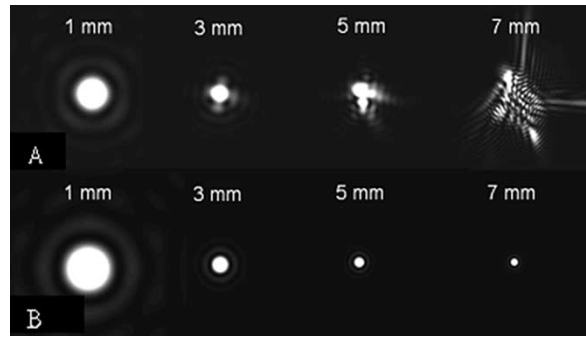


Fig. 3. (a) PSFs of a typical human eye for different pupil sizes, the effect of aberration is clearly apparent. (b) Same eye but with correction of the aberration. One cannot use the increased resolution of a larger pupil without correction of the aberration. Courtesy of A. Roorda, University of Houston, Houston, TX.

quality when the eye's optics are used in reverse to image the retina. So would a static phase plate corrector suffice? Even for an eye with paralyzed accommodation, there are still temporal microfluctuations in accommodation, which can significantly degrade image quality. Hofer [7] has shown that even with static correction of the higher order aberrations the temporal effects can reduce retinal image contrast by 33% and the Strehl ratio by a factor of three. In order to utilize the full numerical aperture of the eye and, hence, maximize the resolution, one must use AO to measure and correct the aberrations in real time.

The idea of using a DM to correct ocular aberrations was first implemented by Dreher *et al.* [8], who succeeded in correcting astigmatism. In this work, the high-order aberrations were not measured, the six-segment DM was simply used to give a static astigmatism correction for use in conjunction with a scanning laser ophthalmoscope. Liang *et al.* [9] introduced the Hartmann–Shack WFS (HS-WFS), which was subsequently improved [10] and automated [7]. This made wavefront sensing broadly accessible to the ophthalmic community. Liang and colleagues at the University of Rochester, Rochester, NY [12], combined a HS-WFS and a DM, demonstrating the first active correction of higher order aberrations.

The striking images, taken by Roorda [12] and Williams, took this imaging capability further and utilized AO to determine the relative number of the three-cone classes that mediate human color vision. Although the relative numbers of long and medium wavelength-sensitive cones can vary over a 50-fold range, all subjects had the same color perception when measured using standard color tests. [13]

Recent work [14] has detailed the applications of AO to closed-loop improvement of confocal laser-scanning ophthalmoscopes. With this imaging modality, real-time video of the retina is obtained and has allowed for *in vivo* visualization of a single blood cell moving through the retinal blood vessels. The retina comprises many retinal layers, and the confocal nature of this device means that only scattered light from the conjugate retinal layer is imaged through the pinhole. The rejection of this out-of-focus light allows for optical sectioning of the retina. Slices through the retina at three different depths are shown in Fig. 4. The high resolution enables individual photoreceptors to be observed. Other vision research groups [15] are building imaging systems that combine the high transverse resolution

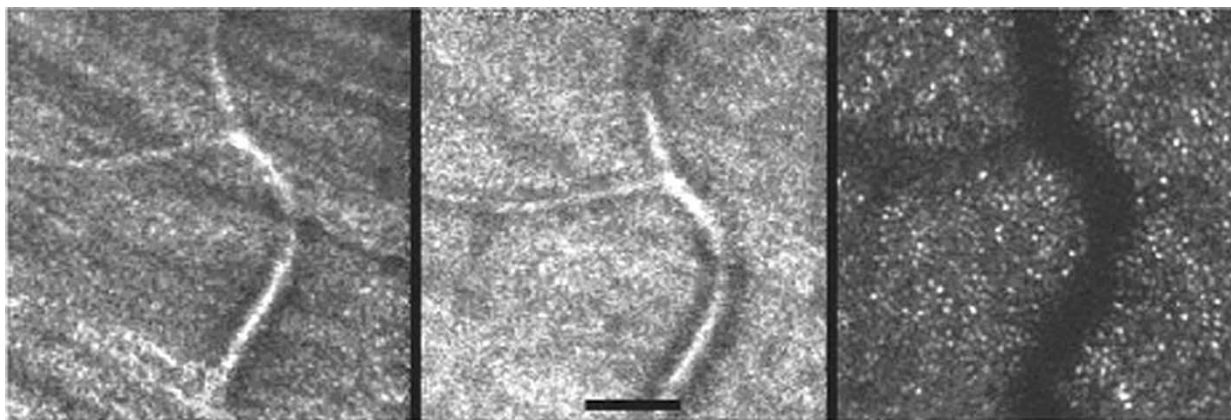


Fig. 4. Axial sections through the retina using the confocal scanning laser ophthalmoscope described in [14]. Sequence starts with the nerve fiber layer (layer closest to the lens) and moves backward. Blood vessels and then the photoreceptor layer come clearly into view. Courtesy of A. Roorda, University of Houston, Houston, TX.

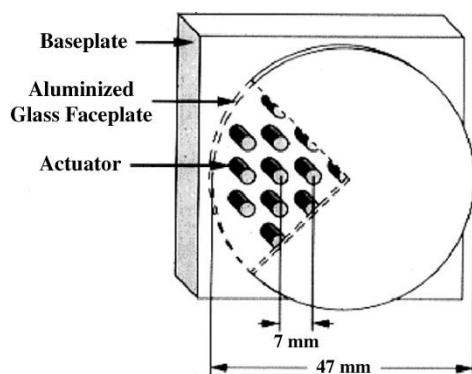


Fig. 5. Cross section through a conventional Xinetics-type DM. An array of actuators sits under a reflective top surface. Application of a voltage to a single actuator causes a localized deformation of the top mirror surface. The actuators are made using either potassium–zirconate–titanate (PZT) or potassium–manganese–niobate (PMN).

afforded by AO with the high axial resolution given by optical coherence tomography (OCT).

III. TYPES OF DMS USED IN VISION SCIENCE

At the heart of an AO system is the DM. All the results presented so far use large, expensive DMs such as those built by Xinetics, Inc., Devens, MA [16], that were primarily designed for the astronomy community. For vision science, the actual operating parameters are much different, but in addition the DM must be made much cheaper and smaller. The DMs for astronomy are expensive, costing over \$100 000 for a 100-channel system. Additionally, they have large apertures (10–30 cm), which for vision requires long optical path lengths to get the required pupil magnification ($\times 15$). To date, the highest order AO system in use for the eye, utilizes a 97-channel PMN Xinetics DM [7]. A cross section through this device and its principle of operation is shown in Fig. 5.

To make compact, low-cost AO-equipped scientific/ophthalmic instruments, however, the price per channel needs to be several orders of magnitude less and also much smaller in diameter, ideally comparable to the diameter of the eye’s pupil

(7–8 mm). Most importantly though, they also lack the required amount of corrective range. The large pupils needed for maximum image resolution can imply peak-to-valley wavefront errors of up to $25 \mu\text{m}$, and this is with defocus corrected prior. The DM, therefore, must be capable of moving at least $12 \mu\text{m}$ (the effect is doubled on reflection). These demands for vision science are much greater than those required for astronomy, where $5 \mu\text{m}$ of DM deflection will usually suffice.

Several other lower cost DM technologies have been explored for vision science. Liquid crystal spatial light modulators (LC-SLMs) rely on a change in refractive index to give the localized phase change rather than changing the profile of the actual DM surface. Vargas *et al.* [17] and Thibos *et al.* [18] used an LC-SLM as their corrective element; it had a pixilated design limiting its spatial resolution. To overcome this sampling issue, commercially available, optically addressed LC-SLMs [19] having 480×480 pixels have received some attention for vision applications. However, even with their extremely high resolution, they still have fundamental limitations, namely, lack of bandwidth, dynamic range, and the need for polarized light.

IV. THE USE OF MEMS FOR VISION AO

As described above, none of the DMs currently available satisfy all the requirements for vision AO. To fulfill this need there has been considerable interest in the use of MEMS mirrors. MEMS promises very low cost, high reliability, and performance with a small system footprint. Perhaps the most well known is the Texas Instruments digital micromirror device (DMD), which comprises up to 1 million 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. To act as a DM, full analog motion is required; in vision science, only two MEMS DMs have been used and experimental results obtained. Both DMs are built from silicon and use electrostatic attraction to provide the mirror deformation. One is a bulk micromachined DM, the other a surface micromachined device, the difference being in the way the mirrors are assembled. Their construction and operation are detailed below.

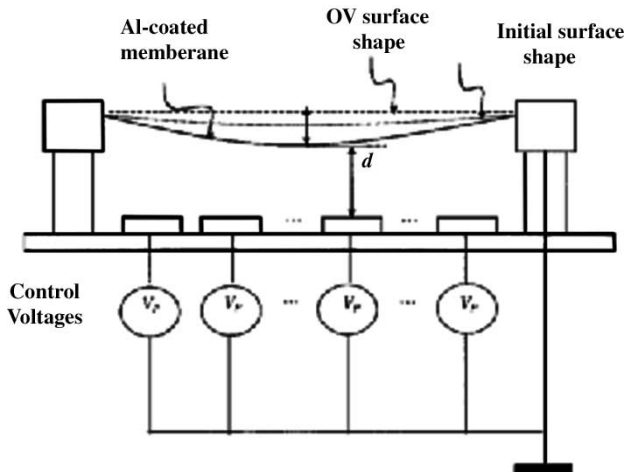


Fig. 6. Structure of the OKO membrane DM. The top dotted line shows the mirrors surface at 0 V. The next lines show the mirrors at half voltage and at full voltage. A random shape can be imparted by assigning different voltages. Note that applying just one voltage deforms the whole mirror surface. From [22].

A. Bulk Micromachined Continuous Surface Membrane DMs

Bulk micromachined continuous surface membrane DMs (MMDM) [20], [21] consist of a flexible reflective membrane lying above a patterned array of electrodes. The electrically grounded top membrane can then be moved by application of a voltage to the underlying electrodes. They basically consist of two parts.

- *The reflective membrane:* Typically made from silicon nitride and coated with an evaporated layer of aluminum or sometimes gold. The choice of a nitride deposition allows for precise control of the membrane stress.
- *The electrode array:* A pattern of aluminum is deposited on a silicon wafer insulated by a 1- μm -thick layer of silicon dioxide. The pattern of the electrodes can be integrated with the control and drive electronics.

A cross section through the OKO Technologies (Delft, The Netherlands) DM [20] is shown in Fig. 6. Several variants of this device have been used for vision AO in several research laboratories. Due to the fact that applying a voltage to one electrode causes the whole mirror surface to deform, the control of the device is rather difficult. Bartsch *et al.* [22] used an iterative algorithm to control the DM. In the first part of their experiment, they found that they could reliably reproduce low-order Zernike modes, but due to the lack of dynamic range and number of electrodes, the generation of higher order modes was limited. Inherent in the MMDM method of operation is that as the spatial frequency of the correction is increased, the available stroke decreases. For example, in low-order modes, one can typically get 1.2 μm of mirror deflection; as the order increases, however, this falls to 0.7 μm . In the second part of their work, they corrected the wavefront aberration in a 33-year-old male. The subject was refracted beforehand to remove defocus and astigmatism in order to reduce the demand on the DM. When the MMDM was used in conjunction with a scanning laser ophthalmoscope, there was an improvement in the transverse resolution by a factor of three. The use of AO enhanced the resolution from 30 to 10 μm . This is still a factor of five greater than the theoretical expectation given by (1).

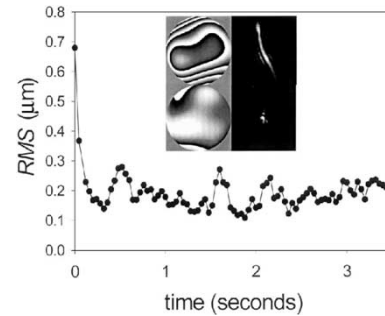


Fig. 7. Example of the correction performance for the OKO mirror. The pupil wavefront aberration and the PSF are shown at the beginning at the end of the AO correction procedure. The rms error was decreased from 0.7 to 0.12 μm for a 4.3-mm pupil. From [23].

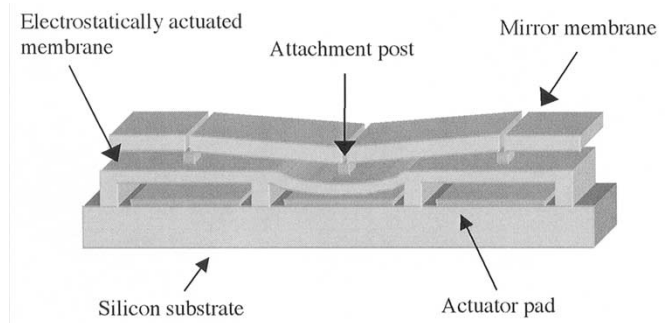


Fig. 8. Cross section of the Boston Micromachines MEMS mirror. The mirror is 3.3 mm^2 with 144 actuators in a square arrangement. The stroke is up to 2 μm at 220 V with a coupling coefficient of 15%. From [26].

Similar work by Fernandez *et al.* [23]–[25] used a 37-electrode OKO device to provide real-time correction of the aberration in the human eye. Instead of using an iterative algorithm, they measured the DM response to each of the electrodes when an individual voltage was applied. From these responses, singular valued decomposition could be used to control the MMDM surfaces. The procedure has the advantage of being much faster than the method outlined in [22]. An example of the PSF improvement on closing the AO loop is shown in Fig. 7. They were typically able to correct a 4.3-mm-diameter pupil with an initial root-mean-square (rms) error of 0.7 μm to a residual of 0.12 μm in a few seconds, corresponding to nearly a threefold increase in the Strehl ratio. They did note, however, that the correction was limited by the spatial resolution of the MMDM.

B. Surface Micromachined Continuous Surface MEMS Mirror

The other form of MEMS DM that has been used in vision AO is the mirror designed by Boston Micromachines Corporation, Watertown, MA [26]. Instead of a continuous flexible membrane as in the MMDM case, this DM allows localized deformations of the top surface rather similar to the type seen with conventional Xinetics types. A cross section through the DM is shown in Fig. 8. This allows for slightly easier control of the DM shape. Additionally, this also allows the correction of higher order modes due to the ability to impart high spatial frequency patterns onto the DM. A thin insulating layer of silicon nitride covers the silicon substrate. A patterned layer of polycrystalline silicon is then deposited to form the bottom, indi-

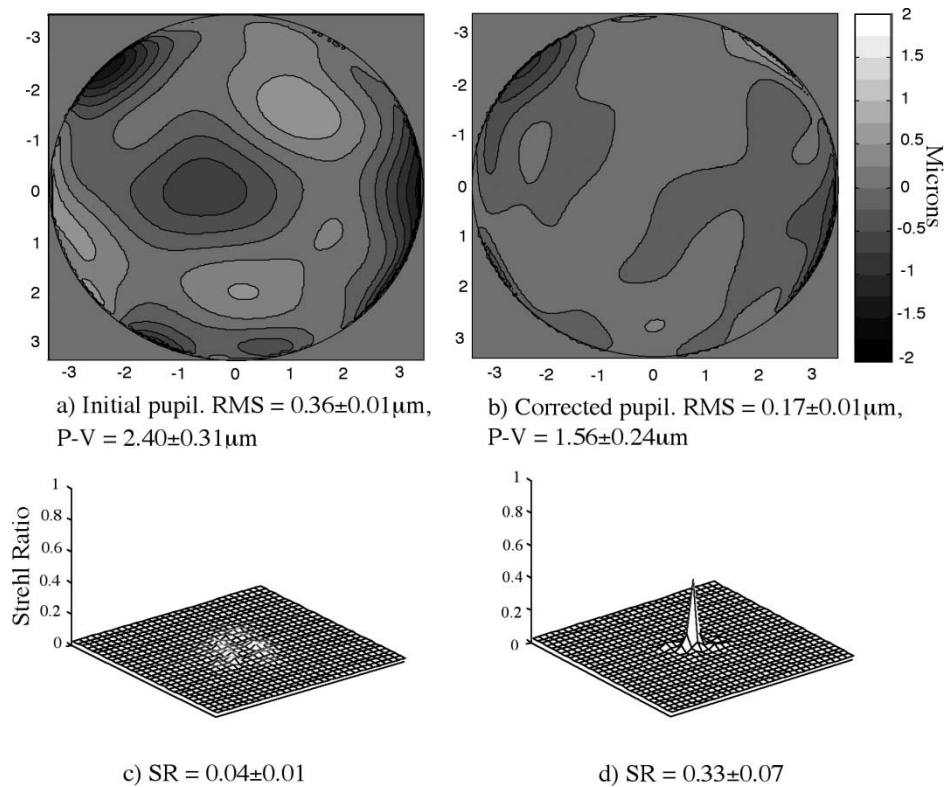


Fig. 9. Before and after AO correction using the Boston Micromachines MEMS mirror for a 6.8-mm pupil. Defocus corrected before both measurements. Average of ten trials used. From [27].

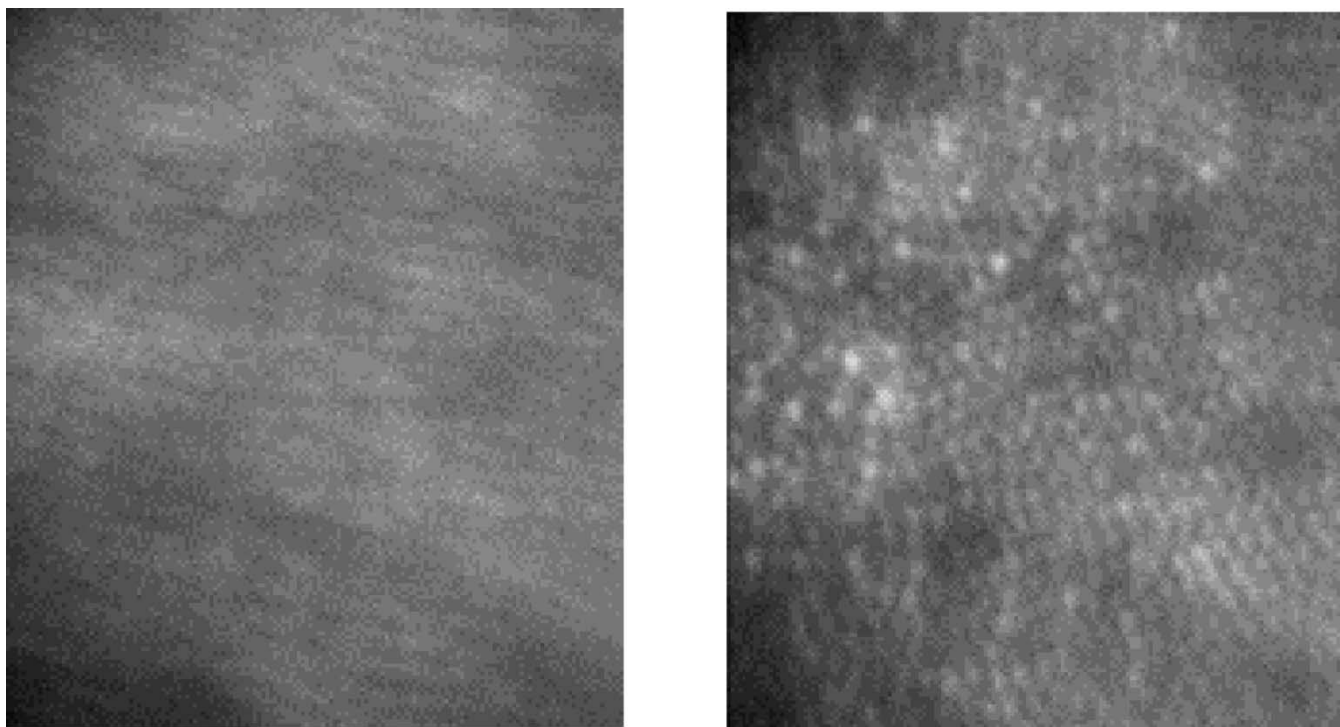


Fig. 10. Before and after AO images of the human retina at an eccentricity of 1° . Photoreceptors are clearly visible in the corrected image. Each is a registered sum of six images. The field of view is 0.3° , corresponding to 75 mm on the retina (horizontal dimension). From [27].

vidually addressable electrodes. On top is the $2\text{-}\mu\text{m}$ -thick upper polycrystalline silicon electrode anchored to the substrate along two opposite edges. The actuator gap is $5 \mu\text{m}$, which gives a mirror movement of $2 \mu\text{m}$. Finally, a $2\text{-}\mu\text{m}$ -thick gold- or alu-

minum-coated mirror membrane is attached to the upper electrode via attachment posts. Biasing the mirror to its midvalue allows for bidirectional motion. A drive voltage of 220 V is enough to give a mirror stroke of $2 \mu\text{m}$.

TABLE I
COMPARISON OF THE DMS DISCUSSED IN THIS PAPER, ALONG WITH
THE REQUIREMENTS FOR AN IDEAL DM

SPECIFICATION	XINETICS INC	OKO TECH	BMC MEMS	HAMAMATSU LC-SLM	IDEAL DM
Diameter (mm)	$\phi = 75$	$\phi = 15$	3.3x3.3	20x20	$\phi = 10$
No. of actuators	97	37	12x12	480x480	100
Surface type	Continuous	Membrane	Continuous Piecewise	Pure Piston	Continuous /Segmented
Stroke (wavefront)	$\pm 4 \mu\text{m}$	$\pm 0.7 \mu\text{m}$	$\pm 2 \mu\text{m}$	10's μms Phase Wrap	$>10 \mu\text{m}$
Response speed	4kHz	0.5kHz	3.5 kHz	13 Hz	100Hz
Operating voltage	100 V	25.5 V	220 V	5 V	A few volts

Recently, Doble *et al.* [27] used such a DM to obtain high-resolution images of the human retina. With this type of DM, it was possible to correct a large pupil (6.8-mm diameter) down to an rms value of $0.17 \mu\text{m}$. The system was arranged in such a way that the performance of the Boston Micromachines device could be compared directly to the existing Xinetics device currently installed in the system. For a 4.8-mm pupil, the performance was shown to be equivalent for both DMs across the three subjects tested. Fig. 9 shows the pupil aberration and corresponding PSF before and after correction for one subject with a 6.8-mm pupil. The rms was corrected to $0.17 \mu\text{m}$ with a $P - V = 1.56 \mu\text{m}$, the SR increasing from 4% to 33%. The use of the large pupil meant that it was possible to see individual photoreceptors corresponding to a transverse resolution of $3 \mu\text{m}$ at a horizontal eccentricity of 1° from the fovea. The images before and after correction are shown in Fig. 10. Examining the image power spectra, there was a fourfold increase in the relative power at the expected cone spatial frequency.

V. CONCLUSION

To date, there has not been a MEMS-based DM that has all the specifications to satisfy the requirements for vision AO. The two MEMS DMs described in this paper are the only ones that have been tested for such an application. The need to make a compact, reliable MEMS DM that has the large stroke and actuator count at a low cost is extremely challenging. Table I lists the parameters of the DMs discussed in this paper and in the final column lists the specifications for a DM with the ideal parameters. New MEMS DM designs such as those discussed in [21] and [28] may, in the near future, deliver a DM which will satisfy these requirements.

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Prof. Williams is a Fellow and a Former Member of the Board of Directors of the Optical Society of America. He received its Edgar G. Tillyer Award for outstanding research in visual science in 1998. He received the American Psychological Association's Distinguished Scientific Award for an Early Contribution to Psychology in 1986. He was awarded a National Eye Institute Research and Career Development Award in 1986 and a John Simon Guggenheim Memorial Fellowship in 1997.