Compact adaptive optical compensation systems using continuous silicon deformable mirrors

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ABSTRACT

Deformable mirrors have been fabricated using microelectromechanical system (MEMS) technology. The mirrors have been integrated into an optical test bed capable of generating static and dynamic aberrations in the beam path. It was found that the DM could be used to improve optical system resolution in the presence of static aberrations. Strehl ratio was measured for the optical system under four test conditions. A Strehl ratio of 0.81 was obtained for the case in which an introduced aberration was compensated by the DM, compared to a Strehl ratio of 0.45 for case in which the aberration was uncompensated and the DM was removed from the optical path. A parallel stochastic gradient descent approach was used for control.

KEYWORDS: Adaptive optics, MEMS, MOEMS, deformable mirror

1. INTRODUCTION

A number of recent research efforts have been aimed at the development of micromachined deformable or segmented mirrors for use in adaptive optics systems. These micromirror devices typically offer higher speed, lower power consumption, smaller size, and lower cost than competing macroscale DMs. Because of these characteristics, MEMS DMs promise to expand broadly the number and type of optical systems suitable for adaptive optical compensation. Presently, AO is used primarily in large astronomical telescopes, military targeting, and high-energy beam-forming – applications for which size, cost, and power are not primary considerations. With the advent of inexpensive, compact DMs, this application space has been broadened to include ophthalmic systems for vision correction and retinal imaging, optical lithography, space-based lightweight telescope systems, laser machining systems, and laser communication systems.

Perhaps the biggest manufacturing challenge associated with MEMS-DM fabrication is the generation of a mirror surface that is smooth enough and flat enough to meet demanding optical requirements. Even when adequate electromechanical behavior has been achieved with these devices, their poor optical quality has generally limited their use in actual AO compensation systems (e.g. the compensated image is of lower resolution than that obtained without the DM in the optical path).

In the work reported here, a MEMS DM having reasonably good optical quality was used to compensate for static aberrations in an optical system. The MEMS DM, manufactured by Boston Micromachines Corporation, is a 140 actuator, continuous silicon mirror. Its optoelectromechanical performance characteristics, which have been detailed elsewhere [1-3], are summarized in Table 1.

Aberrations were generated by a second deformable membrane mirror in the optical path of the test bed. For the experiments reported here, the aberration generating mirror was a 37 actuator mirror manufactured by Flexible Optical BV, which has been described elesewhere [4]. This mirror is relatively flat when it is unactuated, and can provide consderable wavefront aberration when it is actuated.

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Table 1: MEMS DM characteristics

Number of actuators	140
Actuator configuration	12 x 12 Square grid (w/o corners)
Actuator spacing	300μm
Clear aperture of mirror	3.3mm
Effective fill factor	99.95%
Unpowered mirror surface figure	50nm RMS
Unpowered segment surface figure	6.7nm RMS
Inter-actuator coupling	15%
Maximum stroke	2μm
Hysteresis	0%
Drive voltage	200V max
Temporal open loop bandwidth	6.6kHz (-3dB @ 50% full stroke)

2. AO TEST BED

Figure 1 is a schematic and a photograph of the optical test bed. The optical system was built to enable measurement of optical image quality both with and without MEMS DMs. Aberrations can be introduced determinisitcally through the use of a flexible mirror in the beam path. A plane silicon mirror can be interchanged with a MEMS DM in the optical path. Both have front surfaces of uncoated silicon. The plane mirror has roughness of approximately 10 Angstroms (RMS), and is optically flat to within 10 nm (RMS) over the aperture of the beam, as measured using an optical contour-mapping interferometer. The plane silicon mirror was left uncoated, so that its inherent reflectivity would match that of the MEMS DM. Coatings on the MEMS DM and the plane mirror would increase reflectivity, and improve optical performance.

The controller uses a stochastic gradient descent algorithm for optical compensation [5]. In this control approach, perturbations (δu) of uniform magnitude with random sign are applied to all DM actuators simultaneously, while monitoring the change in peak image intensity of the point image (i.e. the perturbed *metric,* J_+). A perturbation of equal magnitude and opposite sign ($-\delta u$) is then applied to the DM actuators and the new perturbed metric is measured (J-). The excitations, u_+ and u_-, applied to a given actuator i at a specific iteration m is the sum of its previous excitation and the prescribed perturbation δu:

and

$$u_{i-}^{m} = u_i^{m} - \delta u_i^{m}$$

$$u_{i+}^{m} = u_i^{m} + \delta u_i^{m}$$

Actuator excitations are then adjusted in proportion to the difference between the two metric measurements, (J_+ - J-), which allows parallel stochastic control. Adjusted excitation u of actuator number i at iteration number $m+1$ is given by:

$$u_i^{m+1} = u_i^{m} + \mu(J_+^{m} - J_-^{m})\delta u_i^{m}$$

where μ is a constant, δu is a perturbation of uniform magnitude with random distribution of sign over both i and m indices, and $J_+ - J_-$ is the difference in metric between positive and negative application of the perturbation δu.

The algorithm is inefficient in comparison to model-based approaches employing Hartmann-Shack wavefront sensor feedback, but its speed, parallelism, and simplicity make it attractive for use in a MEMS DM test bed.

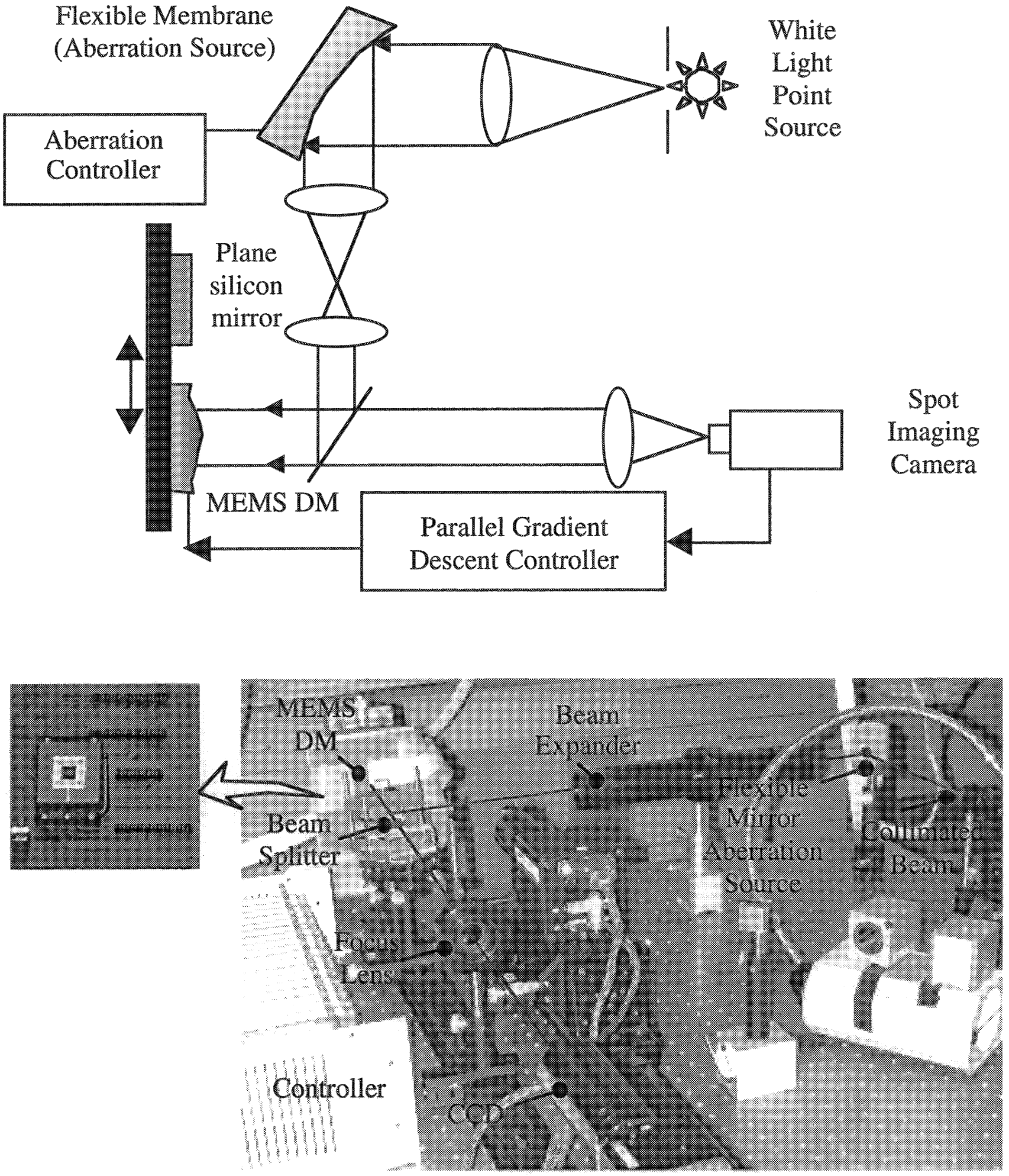

Figure 1: Schematic and annotated photograph of the adaptic optics test bed used for MEMS DM evaluation. A collimated beam of white light from a fiber-optic point source reflects from a flexible membrane mirror that is used either as a plane mirror in its undeformed state or as an aberration source in its deformed state. The reflected beam passes through a beam expander and a beam splitter onto one of two mirrors: a MEMS DM or a plane silicon mirror. The beam passes back through the beam splitter and a lens, arriving at a focus on a CCD camera, which measures lateral position and intensity distribution of the point image.

3. RESULTS

Strehl ratio, the peak intensity of an aberrated point image normalized by the peak intensity of an unaberrated point image, was measured for several test cases:

1. No introduced aberrations, no DM in the beam path (Strehl ≡ 1.0);
2. Static aberration, no DM in the beam path;
3. Static aberration, with DM in the beam path, uncontrolled; and
4. Static aberrration, with DM in the beam path, controlled with AO feedback.

Figure 2 shows captured CCD frames at the image plane of the optical system for the four cases described above.

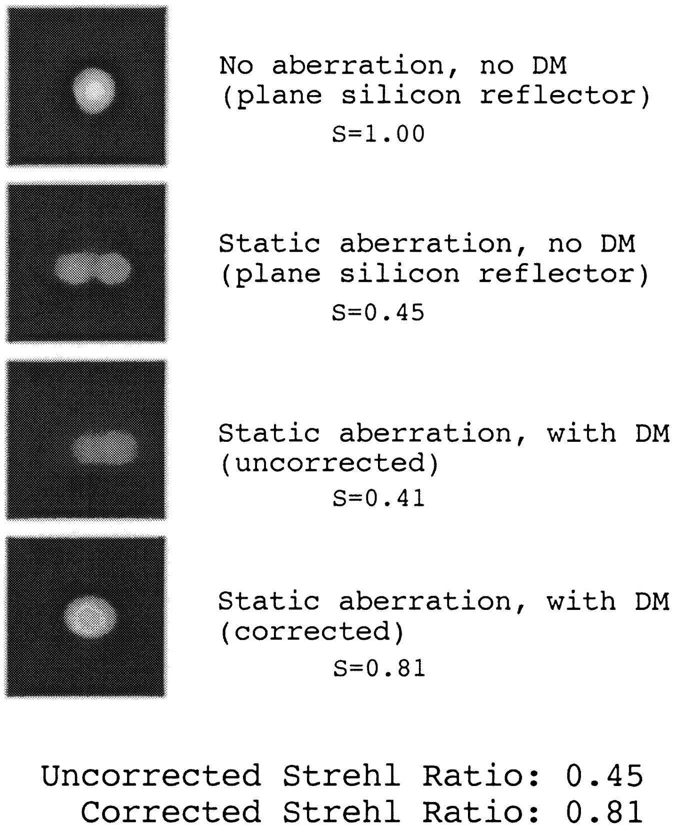

Figure 2: Measured spot images for optical test bed experiments with and without introduced aberrations and with or without MEMS DM control. The top image is an ideal case (given the limitations of the optical system). The second and third images illustrate blurring due to introduction of a static aberration and an uncontrolled MEMS DM, sequentially. The final image illustrates compensation achieved with a contolled MEMS DM.

For these measurements, peak intensity was calculated as a numerical summation of measured gray-scale values within a small aperture surrounding the centroid of the spot image, as recorded by the CCD camera. This value was used as the metric for the gradient descent algorithm and to quantify Strehl ratio.

A detailed graph of peak intensity as a function of iteration number for the final case is shown in Figure 3.

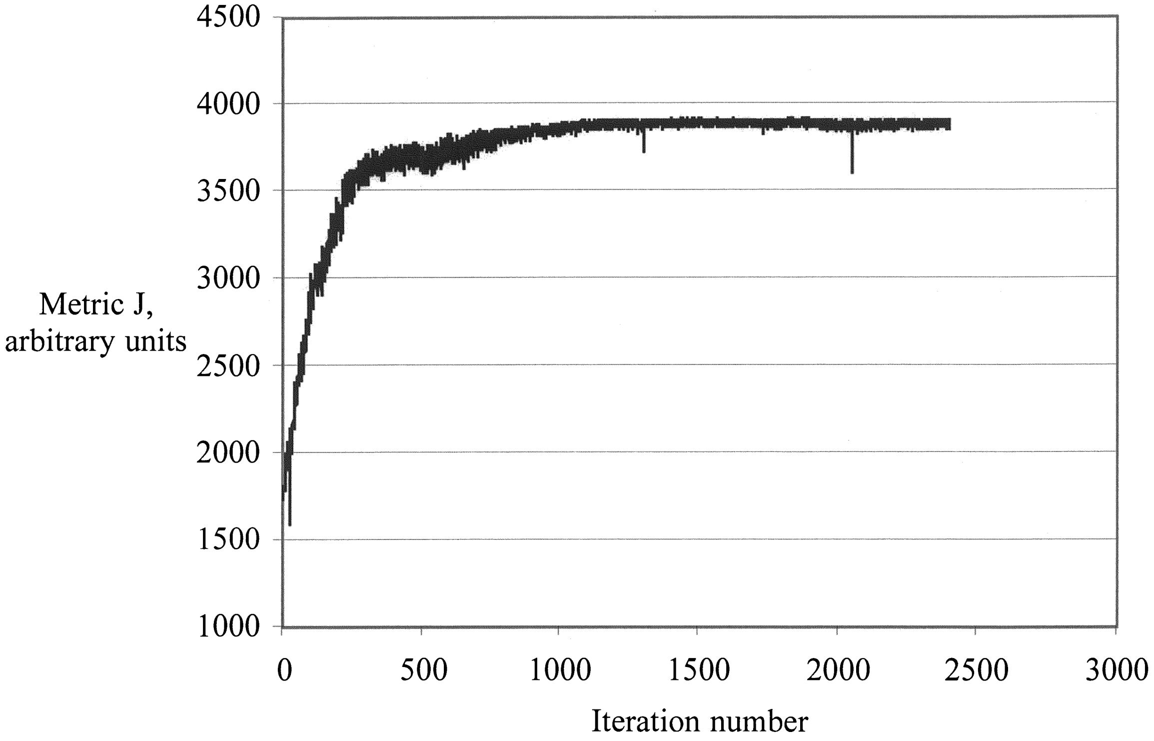

Figure 3: Change in peak intensity of the spot image as measured during closed-loop control using the gradient descent algorithm and a MEMS DM.

4. CONCLUSIONS

In this paper, adaptive optical compensation of an aberrated optical beam using a MEMS DM has been demonstrated. In experiments comparing MEMS DM compensated images to images made by unaberrated beams reflecting from a smooth, flat silicon reference mirror, a Strehl ratio of 0.81 was observed. This represents significant capacity for aberration compensation by the MEMS DM. Future research directions will include adding optical coatings for enhanced DM reflectivity, and adaptive compensation of dynamic aberrations.

The full-scale compact adaptive optics system that has been demonstrated in this work has broad applicability to high-resolution imaging systems subject to beam aberrations.

5. ACKNOWLEGDEMENTS

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