Open-loop performance of a high dynamic range reflective wavefront sensor

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Abstract: Sandia National Laboratory has constructed segmented Micro-Electro-Mechanical deformable mirrors that are under investigation for their suitability in experimental Adaptive Optics systems for the Naval Research Laboratory. These mirrors are fabricated in a hexagonal array and can been constructed with flat surfaces, or with optical power allowing each mirror to bring its subaperture of light to a focus similar to a Shack-Hartman array. Each mirror can use the tip, tilt and piston function to move the focused spots to the reference location, and the measurement of the applied voltage can be used directly to power a similar flat MEMS deformable mirror. Unlike the Shack-Hartman array, this wavefront sensor can detect large magnitude aberrations up to and beyond where the focused spots overlap, due to the ability to dither each focused spot. Previous publications reported on this novel new technique and the electrical specifications, while this paper reports on experiments and analysis of the open-loop performance, including repeatability and linearity measurements.

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1.0 Wavefront Sensors and our efforts

Wavefront sensors, such as the Shack-Hartmann wavefront sensor [1, 2], typically use a lenslet array to focus light onto an imaging camera or quad cell detector. This technique is used as a measure of aberrations in wavefront, as these phase variations are translated to spatial spot displacements on the detector. Astronomical adaptive optics (AO) systems typically operate in the “low light regime” and significant effort goes into maximizing light throughput [1] and maintaining spectral efficiency. Many different variations of Shack-Hartmann sensors have been developed to improve the wavefront sensor performance; however, most of these systems rely on refractive optics [2] which introduces transmission loss through the lens material.

The Naval Research Laboratory (NRL) is actively involved in the development and testing of new and novel AO components and systems to support upgrading the capabilities of the Naval Prototype Optical Interferometer (NPOI) located in Flagstaff, Arizona. NPOI is the world’s only 6 element interferometer capable of operation in the visible wavelengths. Currently, the array uses siderostats for light collection that limit the entrance beam to a few tens of centimeters. This helps to avoid atmospheric turbulence, but limit the visible magnitude of celestial objects to roughly 6.

The array is undergoing an upgrade to 1.4 meter telescopes in an effort to dramatically increase the sensitivity. These 1.4 m telescopes necessitate the use of AO to compensate for the atmospheric turbulence. Additionally, population of nearly two dozen stations with meter class telescopes is cost prohibitive, so the array will be reconfigurable by using portable telescopes. These telescopes are constructed of light weight carbon fiber for both the structures and the optics, and the AO systems are mounted within each of the telescopes [3].

Small, lightweight deformable mirrors are currently being investigated for inclusion in the portable AO systems. Most mirrors considered are Microelectromechanical (MEM) technologies. These devices can be manufactured at low cost to meet a wide range of applications and can be constructed as either segmented or continuous face sheet mirrors. One of the first MEMs mirrors to become readily available was the 37 actuator 15mm OKO mirror which has been well characterized [4].

2.0 The Sandia MEM mirror

Segmented mirrors developed at Sandia National Laboratory (SNL), include mirror arrays of the type shown in Figure 1 that are fabricated using the Sandia Ultra-planar Multi-level MEMs Technology (SUMMIT™). The MEMs mirror array shown in figure 1 has 61 individual hexagonal segments with each reflective segment mounted on 3 large-throw electro-static actuators. The diameter of the actuated region of the mirror is 3.9 mm with each segment being approximately 0.5 mm measured across the flats of the hexagon [5]. The chip containing the mirror utilizes a 20 x 20 pin grid array and is mounted to the controller using a Zero Insertion Force (ZIF) socket.

The overall shape of the mirror surface is controlled by 183 actuators which allow the 61 individual hexagonal segments to be positioned in tip, tilt and piston. While unpowered, each mirror segment is in a default state where there is a slight amount of tip, tilt and piston between each mirror due to slight variations in actuator manufacture. The mirror must be powered and the appropriate voltages applied to flatten the mirror and phase up all mirror segments. In the wavefront correction version of the mirror, surfaces of the individual mirror segments are flat; however, these mirror segments can also be manufactured with a powered surface which can focus light.

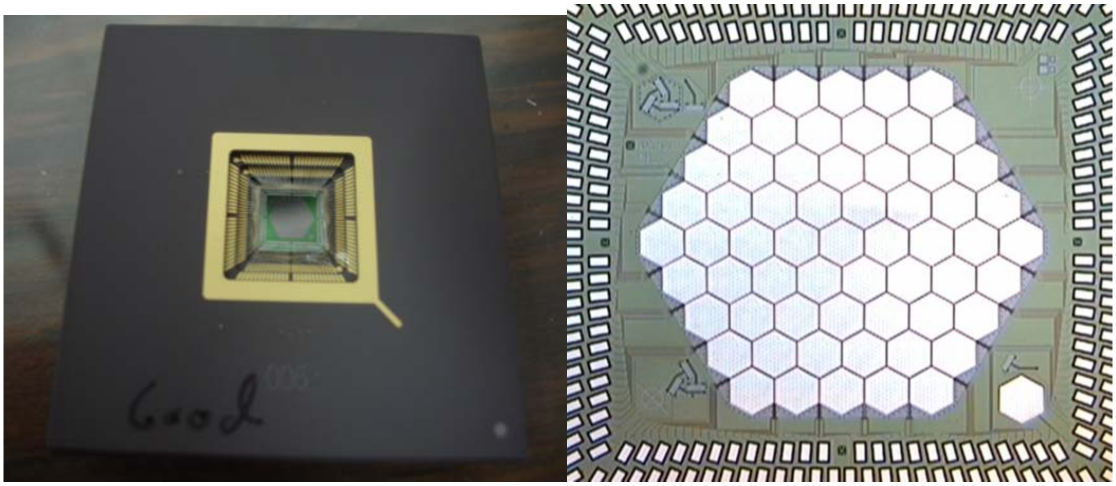

Figure 1: (Left) Photograph of the MEM deformable mirror developed and manufactured by Sandia National Laboratories. (Right) Schematic of the actuator layout for the device. Notice that the reference mirror segment can be seen in the lower right and the actuator arrangement in the lower left. (Courtesy Sandia National Laboratories).

The optical characteristics of the mirror were evaluated using a Wygo interferometer at Sandia National Laboratories and the reconstruction of two of the low order modes are shown here. Figure 2 shows the mirror biased to provide a nearly flat figure and biased to provide defocus. Here the individual segments of the mirror can be clearly identified. This is indicative of there being a small height offset between the segments.

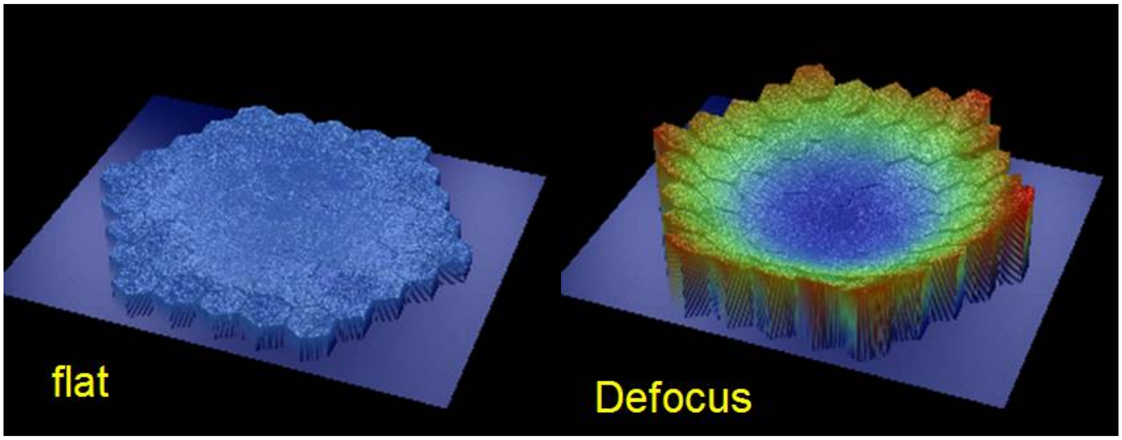

Figure 2. (Upper) Wygo images that show a nominally flat mirror with no actuator voltages applied. (Lower) The mirror under bias to apply an overall positive curvature.

The mirror itself is capable large dynamic range, far exceeding the range where the beams can overlap. In an experimental setup, a camera was placed a distance of 60 mm from the mirror, which was illuminated with a collimated beam. The voltage on one actuator of one mirror on the far edge of the mirror array was adjusted to move the beam across the array and overlap with the beam on the opposite edge.

Measurements of the maximum stroke for the mirror segments showed that operation at 150 V delivered actuator stroke of 26.7 microns. The maximum stroke corresponds to about 40 waves at 632 nm wavelength demonstrating its suitability for operation with large aberrations. The stroke verses voltage and tilt angel verses voltage curves are shown in Figure 3.

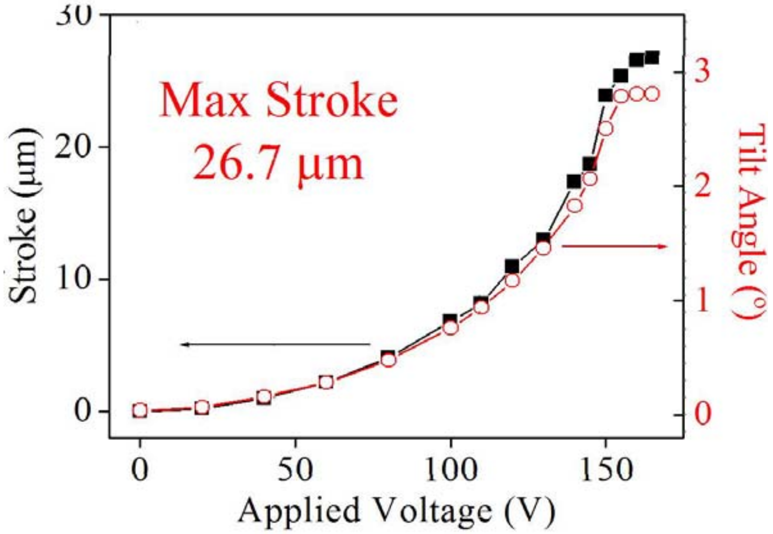

Figure 3. Plot of the measured stroke for the mirror.

3.0 A reflective wavefront sensor

Manufacturing the individual mirror segments such that they have optical power is the key to using this mirror as a wavefront sensor. When an array of curved mirrors is illuminated by collimated light, a well defined set of spots that can be focused onto a camera is created. The position of the individual spots is proportional to the angle of the wavefront. Movement of a single spot and the effect of a small aberration to the mirror are shown in Figure 4.

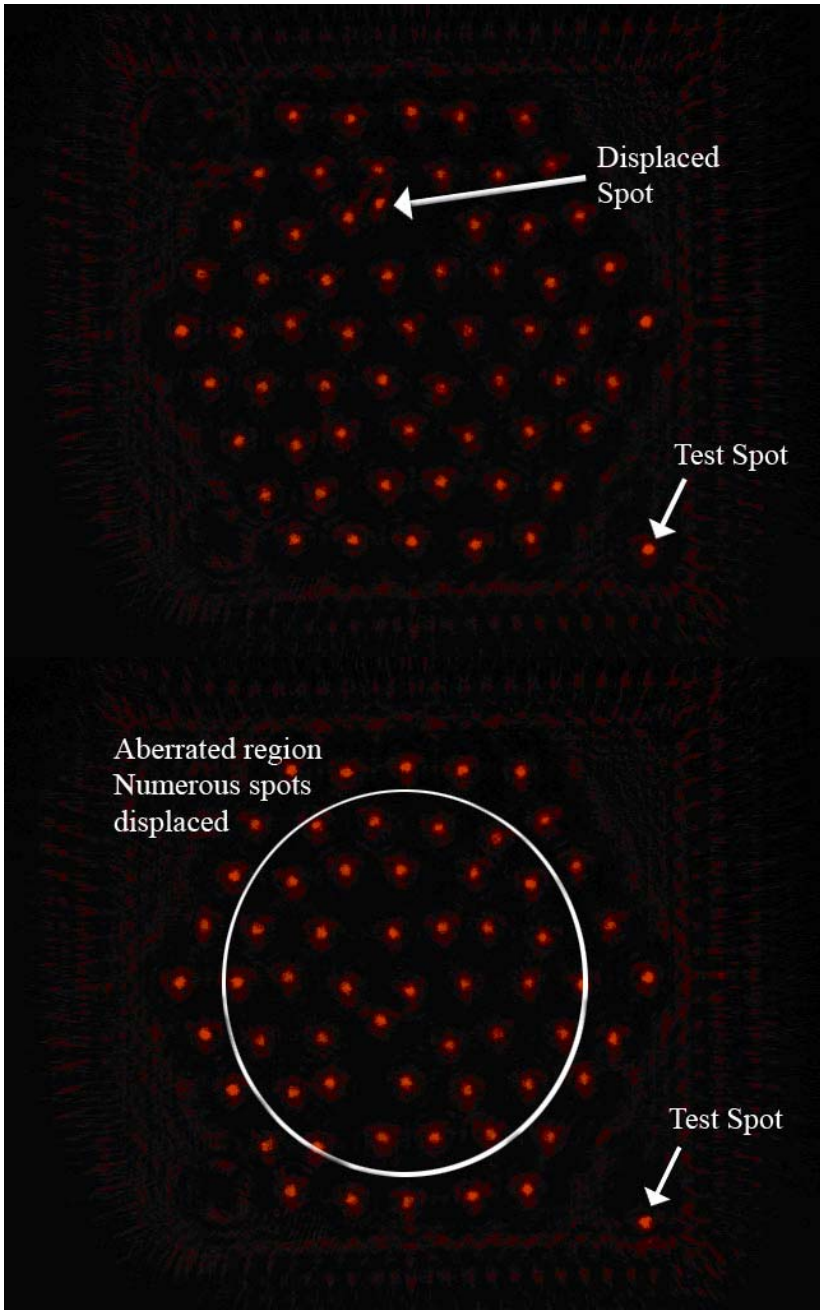

Figure 4. (Upper) MEM deformable mirror showing the effect of moving one of the mirror segments. (Lower) MEM deformable mirror showing the effect of a small aberration being introduced into the collimated beam. The spot to the lower right of each of the figures is from the test mirror.

By comparing the position of each of the spots from the mirror to their reference locations a compensating voltage can be applied to move the spots back to the reference position. The wavefront tilt for each mirror segment is then described by the map of the voltages used to restore the array of spots to their reference location.

4.0 Open-loop operation

Using the 20 x 20 grid array ZIF socket coupled with a controller card, high voltage amplifier and ribbon cable interconnects as described in Figure 5, several individual actuators were dithered to determine the open loop positioning accuracy.

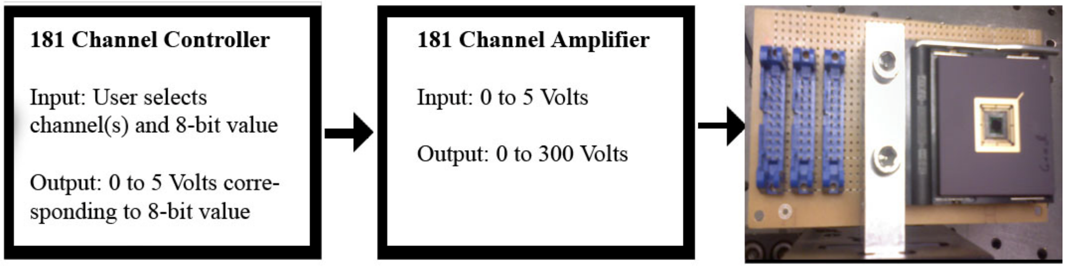

Figure 5. Block diagram of controller

The optical setup for this experiment is shown in Figure 6. A laser source was collimated and used to illuminate the reflective wavefront sensor. An array of spots similar to those in Figure 4 was created and imaged directly onto the CMOS camera where the displacements were measured in the focal plane.

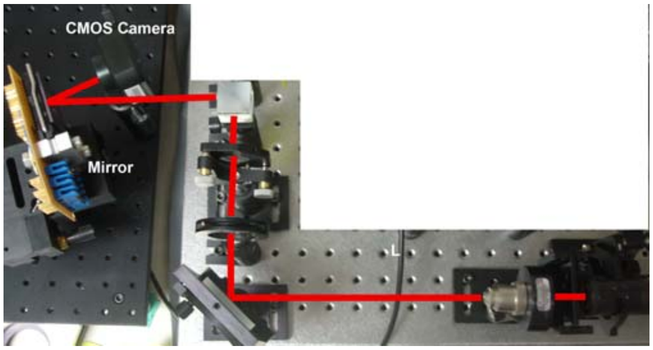

Figure 6. Optical setup for testing repeatability. Laser source is collimated, reflected off the reflective wavefront sensor and is viewed on the CMOS camera.

Figure 7 shows the open loop positioning accuracy. The displacement versus voltage was measured using a CMOS camera located 100mm distant from the MEMs array. Spot displacement was measured over an applied voltage range from 0 to 50 volts in order to keep the spots in the field of view of the camera with the optical arrangement. This voltage range induced spot displacements of between 0 to 500 pixels. The camera pixels were 6.7µm across and the diameter of each spot covered approximately 6 pixels. Each displacement point is the average of 11 samples taken for a given applied voltage.

The displacement voltage curves seen in Figure 7 show nonlinear behavior, and that there is a difference in the gain between individual actuators. However, the repeatability for a given displacement with voltage is very high, typically on the order of a 1/5 pixel.

The MEMs actuators operate by electrostatic attraction so the actuator movement is anticipated to follow the square of the applied voltage [6]. As such, the differential form of the displacement of the spot on the camera can be described as:

$$dD = (kf_L V + \delta)dV \tag{1}$$

where D is the displacement of the spot, f_L is the focal length of the individual mirror segments, V is the applied voltage, and k, δ adjust for the amplifier gain, effects of other actuators attached to the mirror segment, and offsets.

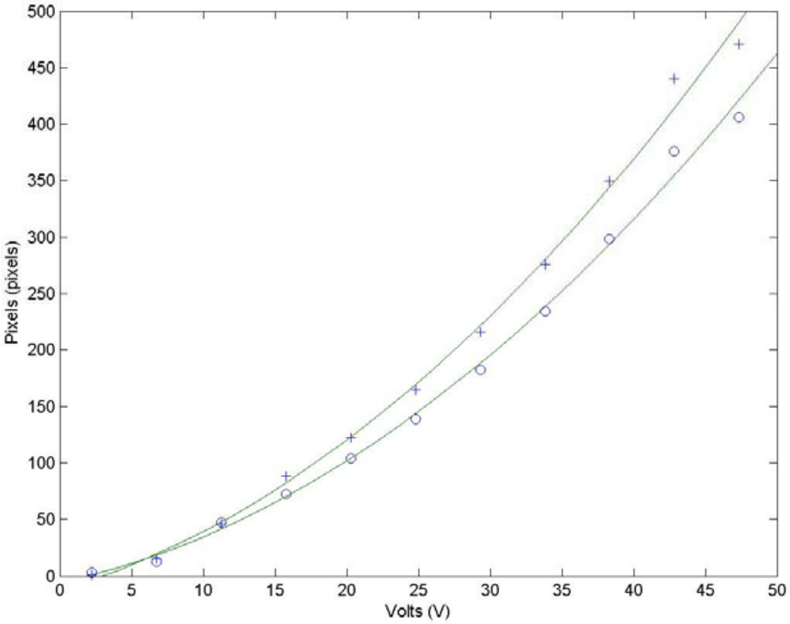

Figure 7. Displacement versus Voltage plots for two different actuators with polynomial fits

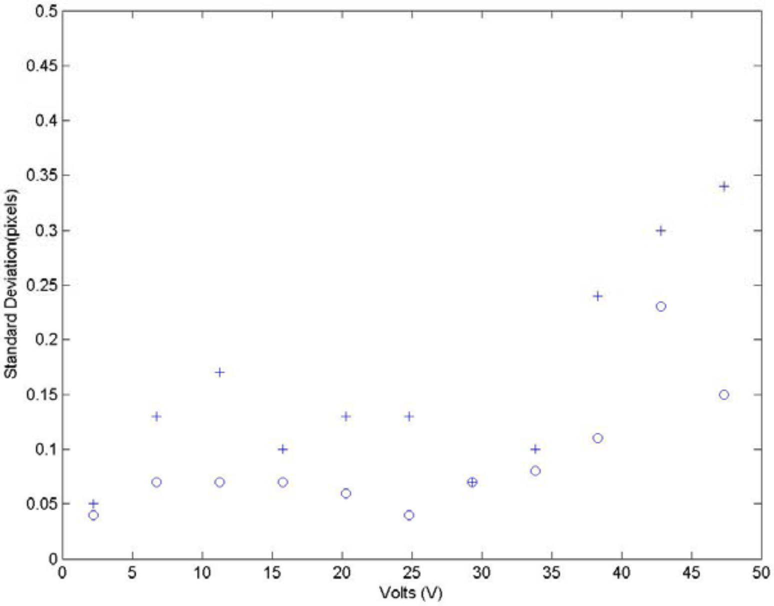

Figure 8. Plot of the standard deviation of the position. Measurements were taken during open loop operation.

5.0 Summary and future

In this paper we have described a reflective MEMs wavefront sensor capable of sensing significant wavefront aberration. The open loop positioning has a standard deviation of less than 0.4 pixels, however, each mirror segment has its own gain that must be compensated.

Work will continue on these mirrors including the integration of these mirrors with current adaptive optics system and overall performance will be measured.

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