Scaling up of the Iris AO segmented DM technology for atmospheric correction

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ABSTRACT

Adaptive-optics correction of atmospheric turbulence requires deformable mirrors with hundreds to thousands of actuators. Since May of 2008, Iris AO has been developing microelectromechanical systems (MEMS) fabrication processes to support the manufacture of 500-3000 actuator DMs. The DM technology is based on a proven, commercially available, 111-actuator, 37-piston/tip/tilt segment DM. This paper presents an overview of the MEMS design and discusses challenges in scaling DMs to thousands of actuators. It will show development progress towards building a 489-actuator, 163-PTT-segment DM and preliminary results of a 925-segment actuator array.

1. INTRODUCTION

Correcting the high spatial and temporal frequency optical aberrations commensurate with atmospheric turbulence places challenging speed and actuator count requirements on deformable mirrors (DM) [1]. Desire for good correction off of Zenith and for horizontal-path applications further increases the number of actuators required. To meet these requirements, DMs with hundreds to thousands of actuators are required that can operate at a minimum of kilohertz rates. Branch points that occur in cases of high turbulence further complicate requirements as phase discontinuities are necessary to correct these.

To meet these needs, Iris AO has been developing a 489-actuator, 163-piston/tip/tilt (PTT) segment DM. The following sections describe the core segmented DM technology the development is based on. Development progress of the S163-X DM follows as well as a demonstration of pathfinding research into building 1000-PTT-segment class DMs. The paper will close with a brief description of some of the challenges that will be faced with scaling MEMS DM technologies to 3000-10,000 actuators.

2. SEGMENTED DM TECHNOLOGY BACKGROUND

The core microelectromechanical systems (MEMS) DM technology Iris AO has been developing is shown in the schematic in Fig. 1a. Thirty-seven of these 700 µm-diameter segments are tiled into an array to create S37-X DMs as shown in the die photograph in Fig. 1b [2]. Each of the segments are actuated by electrostatic forces created by three electrodes placed under the actuator platform. The actuator platform, held at ground potential, creates the top electrode of a parallel-plate capacitor with each of the underlying electrodes. By varying analog voltages on the electrodes, the segments can be positioned in three degrees of freedom - piston, tip, and tilt. The maximum stroke of the device is set by the gap between the actuator platform and the underlying electrodes, and is approximately one-fourth of the gap. Normally creating large gaps necessary for 8 µm stroke devices and greater is a difficult challenge for MEMS devices as this is usually done by depositing a thick sacrificial layer between the top and bottom electrodes. Instead, the Iris AO DM segments create the large gap by engineered residual stresses in the bimorph flexures. During the microstructure release step, the flexures elevate the actuator platform because of the engineered tensile residual stresses in the upper layer of the bimorph flexures. By design, the flexures have low temperature sensitivity; they are purely used for passive mechanical support of the actuator platform.

Thick (20-50 µm) single-crystal-silicon mirror segments are assembled onto the actuator platforms to provide a robust, high-optical-quality substrate onto which a large variety of optical coatings can be deposited. To date, protected-aluminum and gold coatings are standard. Dielectric coatings are currently being developed for laser-guides-star uplink correction as well as protected-silver coatings [3].

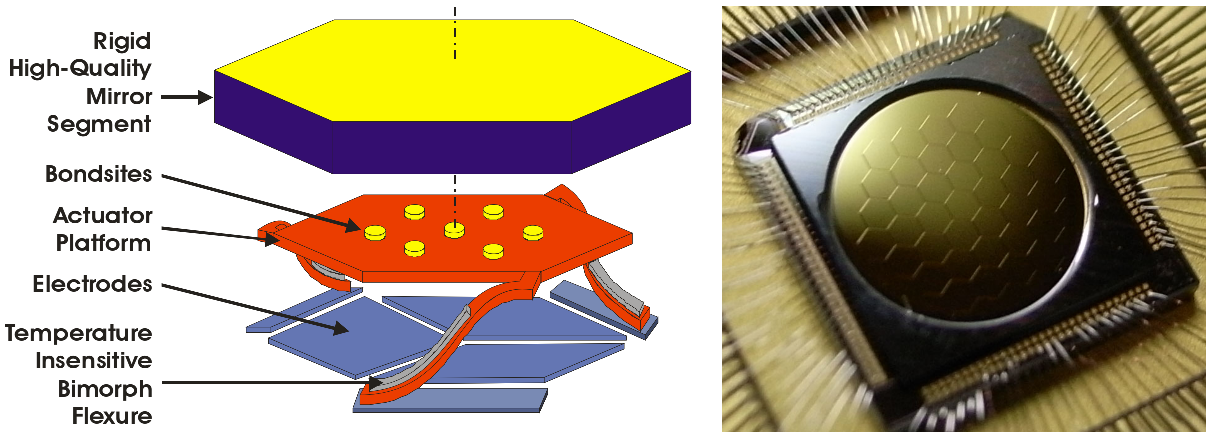
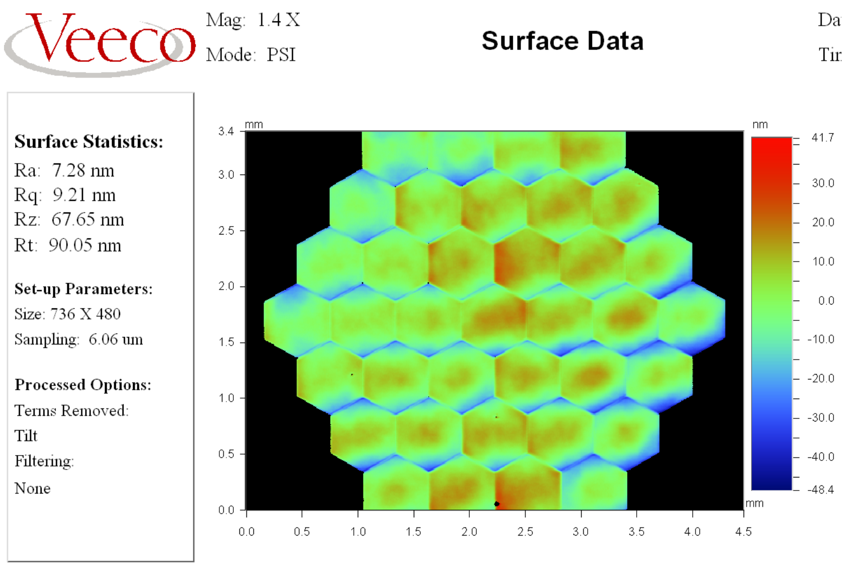


Fig. 1. a) Schematic diagram of an Iris AO DM segment. The diagram of the 700 µm diameter segment (vertex-to-vertex) is highly exaggerated in the vertical direction. Tens, hundreds, and even thousands can be tiled in an array. b) Die photograph of a 111-actuator 37-piston/tip/tilt-segment DM with 3.5 mm inscribed aperture. Photo courtesy of Takayuki Kotani, Paris Observatory.

Despite the thick mirror segments, step responses are fast with a slightly underdamped response around 2.3 kHz. Rise and fall times are 120-140 µs for 20-80% and 170-200 µs for 10-90% respectively for steps of 1.6 µm [4].

In general, electrostatic actuation is nonlinear and further complicating the response are the interactions between the three electrodes and mechanical structure. Furthermore, parallel-plate actuators can be prone to over-voltage failures unless proper limits are set in place. To dramatically simplify operation, Iris AO has developed a factory-calibrated precision open-loop controller to position the DM segments [5]. Instead of commanding highly-nonlinear voltage values, the user simply enters in piston/tip/tilt commands in microns and milliradians. This intuitive controller not only simplifies control, it linearizes the DM positioning and further calibrates out any manufacturing variations between segments and across mirrors. The controller limits the mirror positions to the safe operating region, so there is no risk of a position command placing excessive voltage on an actuator. An example of the positioning capabilities of the controller used for the case of open-loop flattening is shown in Fig. 2. Residual surface figure errors are a mere 9.2nm *rms* for this protected-aluminum coated mirror.



Mag: 1.4 X
Mode: PSI

Surface Data

Da
Tir

Surface Statistics:
Ra: 7.28 nm
Rq: 9.21 nm
Rz: 67.65 nm
Rt: 90.05 nm

Set-up Parameters:
Size: 736 X 480
Sampling: 6.06 um

Processed Options:
Terms Removed:
Tilt
Filtering:
None

Title: FSC37-01-07-0614
Note: Open-Loop Flattened

Fig. 2. Demonstration of open-loop flattening using the factory-calibrated precision open-loop controller developed by Iris AO. Residual surface figure errors are only 9.2 nm rms for this protected-aluminum coated DM with 25 µm-thick mirror segments.

3. 489-ACTUATOR, 163-PTT-SEGMENT DM DEVELOPMENT PROGRESS

The S37-X series of DMs lacks the spatial fidelity to make it useful for most applications requiring atmospheric turbulence correction. It does, however, provide a solid foundation onto which to build from. The next generation DM Iris AO is developing is a 489-actuator, 163-PTT-segment DM. A diagram of the S163-X 7.7 mm inscribed aperture is shown in Fig. 3a. Fig. 3b shows a die photograph of one of the S163-X actuator chips. This chip includes everything up to and including the bondsites as shown in Fig. 1a. The mirror segments are fabricated on a separate wafer.

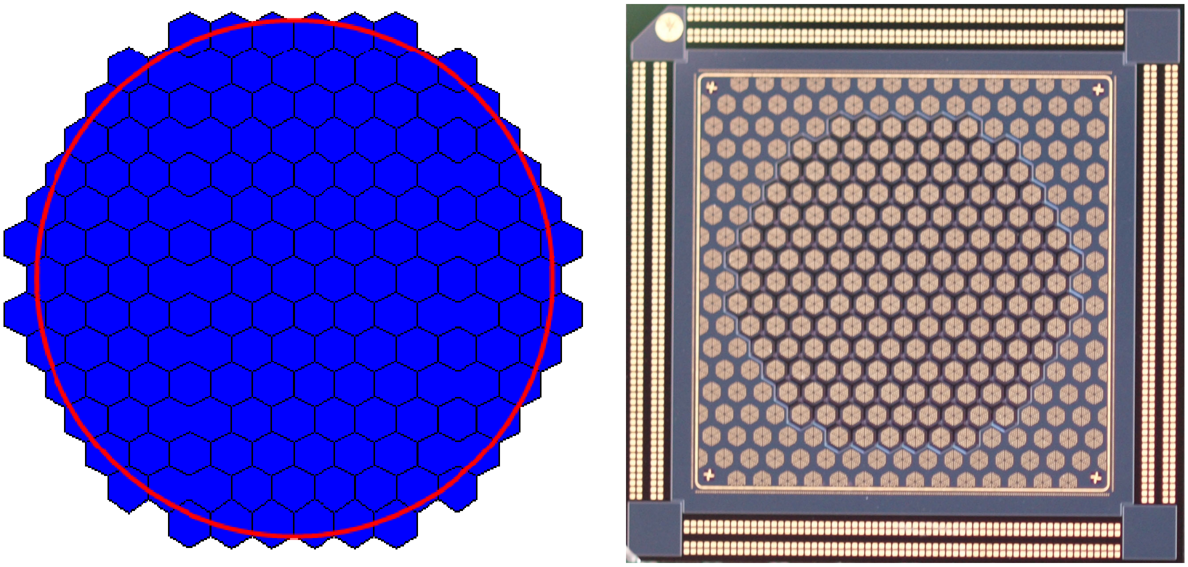


Fig. 3. a) Schematic diagram of the S163-X DM array. The inscribed aperture, drawn in red, is 7.7 mm for this DM. Segments that lie outside of the aperture have been eliminated from the design. b) Die photograph of a prototype 489 actuator, 163-piston/tip/tilt-segment actuator chip.

The fundamental segment design is identical to that of the S37-X DMs. For the S163-X DMs, however, the fabrication is now done entirely by Iris AO and a small set of process vendors. Development of the S163-X DMs began in May 2008 with the first of three planned fabrication runs. The first fabrication run was a mechanical only run that included S37-X and S163-X DMs as well as a pathfinding 925-segment array. It did not include any of the wires necessary to connect to the electrodes on the chip. This fabrication run was used primarily to verify the design, run the majority of the actuator process through completion, and to assess mechanical yield of the actuator platforms. The materials from this fabrication run are further being used to develop the flip-chip bonding processes used to assemble mirror-segment arrays onto the actuator-platform arrays. Initial mechanical yield of the actuator platforms was a very encouraging 100% for the small sample of chips that were released. Although an overwhelming success from the standpoint of yield, many additional steps are required to build functional DMs that will reduce yield.

A second run including a dedicated wiring layer was completed in March 2009. This fabrication run showed a 98% electrical yield, with strong concentrations of defects rather than being distributed uniformly across the wafers. Electrical yield was assessed with S37-X actuator arrays included on the same wafers to act as test devices until a dedicated electrical-tester and probe station are completed. It is believed that the yield reductions came primarily from a relatively thin passivation layer used to electrically isolate the wires that run under the electrodes. In the third fabrication run of this three-run development, this part of the fabrication process will be improved upon.

The first of two mirror-wafer fabrication runs for the S163-X DMs is complete as well. This process has always been run by Iris AO, so only two fabrication runs of these were planned.

With materials from the actuator and mirror wafer fabrication runs, Iris AO is running through the backend (chip-level) processing, which includes flip-chip assembly, clearing the bulk silicon above the mirrors, microstructure release, optical coating, and packaging. Concurrently, an electrical-probe-testing station is nearing the final stages of fabrication to test the S163-X DMs at the die level. After all of the fabrication processes have been run through, the third fabrication run will commence. This third run will be dedicated to the S163-X DMs only, marking the transition from initial prototyping to manufacturing.

4. 925-SEGMENTPATHFINDING DM DEVELOPMENT PROGRESS

As described in the prior section, the prototyping fabrication runs for the S163-X DM included a pathfinding 925-segment design as well. The goal of this design was to exercise the fabrication processes on much larger arrays in order to assess the challenges when scaling to DMs with thousands of actuators. To keep costs down by leveraging existing infrastructure, the 925-segment DM array had banks of actuator platforms electrically ganged together so they could be operated with a small number of channels. Doing so made it possible to directly mount the pathfinding actuator arrays directly onto a printed circuit board as seen in Fig. 4.

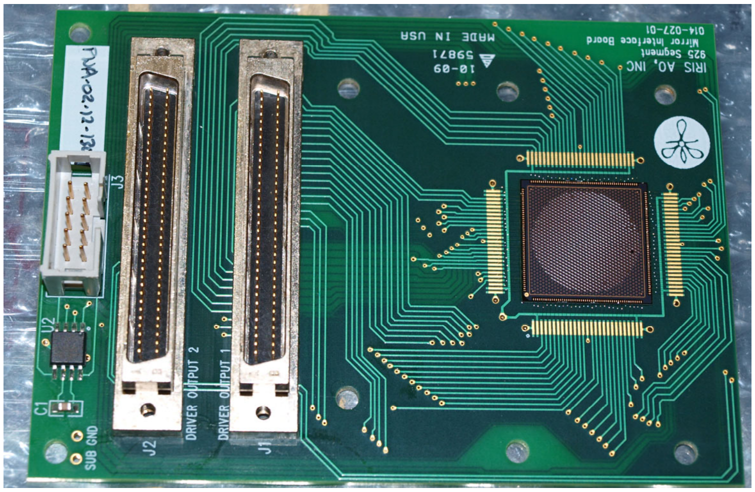


Fig. 4. Photograph of a 925-segment pathfinding array mounted and wirebonded to a printed circuit board. The chip size is 20.08 mm on a side. By electrically ganging banks of actuators, the entire chip can be operated with only 92 driver channels.

The actuator-platform mechanical yield for the best of four chips that were released was 99.3% (e.g. only 6 damaged actuator platforms). A few damaged actuator platforms are visible in the array in Fig. 4. These were primarily due to handling issues of these large chips. Since this was the first time chips of this size have been fabricated, the necessary infrastructure was not in place.

Fig. 5 demonstrates actuating different banks of actuators with a sequence of measurements taken with a white-light interferometer.

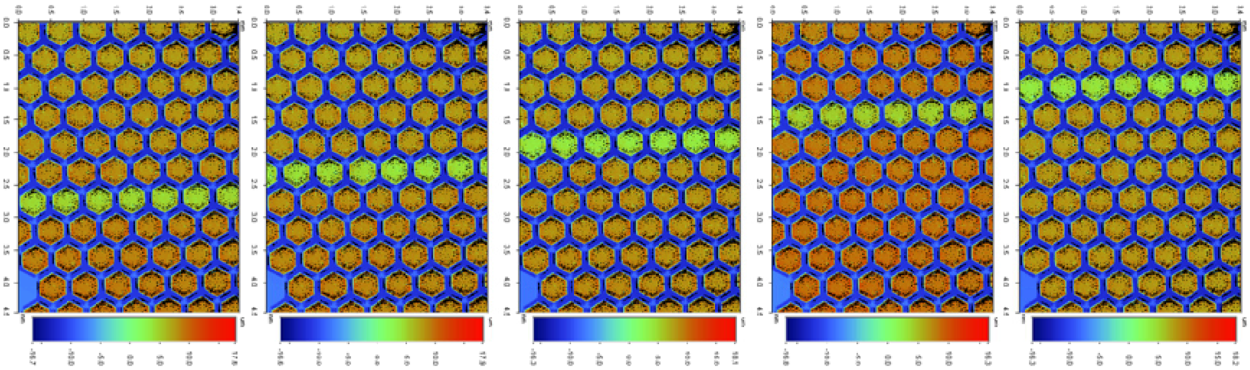


Fig. 5. Measured actuator platform heights for a test sequence where separate banks of the 925-segment path-finding array actuators have been actuated.

5. DM SCALING CHALLENGES

Fabricating the 925-segment pathfinding arrays has shown that the biggest challenges to be faced with building 3,000-10,000 actuator arrays will be segment yield and electrical interconnect.

Building larger and larger arrays will require dramatic yield improvements in order to build a DM with no bad actuators. As an example, a 1000-segment (3000 actuator) DM with, an impressive by current standards, segment yield of 99.5%, would result in less than 1% of the devices fabricated being fully functional. This is clearly not a viable option. Only when segment yields reach 99.75% would array yields reach more than a few percent. Even higher yields are certainly possible, but require additional development, thus adding cost. Until the fabrication processes improve, users of MEMS DMs should consider the impact a single or even a few bad segments have on the performance of the AO system in question. Allowing a few bad segments dramatically increases the yield of these devices. In the case of the segmented DMs Iris AO manufactures, most often the bad segments can be tilted at large angles so that the effects of these segments can be eliminated with simple optical stops.

Electrical interconnect becomes a challenge for larger DMs, especially as actuator counts reach 10,000. The materials used on the MEMS DMs support incredibly small pitches (10 µm or less) for high-voltage wires (200V) on the chip. Once the wires escape the high-quality dielectrics and are routed to wirebond pads, the pitch increases an order of magnitude to 100-200 µm. Escaping from the ceramic package onto a printed circuit board increases the pitch to 600 µm or more. Finally, running off the interface board to drive electronics through high-density wires can lead to pitches of 1 mm. Thus, it is easily possible that a 10 m wide swath of high-voltage, high-density ribbon cable will be needed to connect a rack of drive electronics to a 10,000 actuator DM. Strategies to increase densities at all levels and ways to bring the electronics closer to the DMs will be required to make this approach more practical. These strategies can include means to reduce voltage in order to reduce electric fields or eliminating one or more tiers of interconnect between the drive electronics and the DM. The ultimate strategy of integrating electronics directly with the MEMS DMs is a very large challenge on many technology fronts. An immediate problem is that the high-voltage circuits necessary to drive MEMS actuators have a larger footprint than the DM actuators they drive. This mismatch forces at least one layer of additional interconnect to realize.

6. FUTURE DM DEVELOPMENT

To further increase AO system performance for atmospheric correction, Iris AO plans to build larger and faster mirror arrays. The next DM array on the technology roadmap will nominally be a nearly 1000 actuator, 331-PTT-segment DM with the same segment size as the S37-X and S163-X DMs. Beyond that will be a 3000+ actuator 1015-PTT-segment DM. For 1000-segment class DMs, the segment diameter will most likely be reduced to 600 µm.

Another area for development is to reduce latencies in the factory-calibrated position-controller and drive electronics, and to increase the DM mechanical response speed. Existing update rates for the S37-X DMs are approximately 3 kHz, or roughly 9 µs per segment. This includes the PC-based PTT controller and time to write to the drive electronics using a PCI-bus digital IO card. As the number of segments increases, we can expect the time to increase correspondingly using existing serial processing techniques. We expect that code optimization in the coming year will reduce this to perhaps as good as 5 µs per segment. Still, this latency is far too great for the larger DMs we intend to develop. Fortunately, the segmented DM lends itself naturally to parallel processing. In the short term, Iris AO plans to take advantage of parallel processing and multicore processors to reduce latencies. In the long term, Iris AO plans to implement its factory-calibrated PTT controller in FPGA hardware to take advantage of massive parallelization. Once this occurs, the dominant factor will be the mechanical DM response. To that end, Iris AO has begun preliminary work on increasing actuator stiffness and reducing mirror mass.

7. SUMMARY

To better meet the needs of atmospheric correction, Iris AO is actively developing the S163-X DM, a 489-actuator, 163-PTT-segment DM. The S163-X DM is based on the proven S37-X series of DMs. Fabrication process development of the larger devices has been very successful to date for preliminary tests. The backend processes are currently being developed to assemble, release, optically coat, and package the S163-X DMs.

8. ACKNOWLEDGEMENTS

The authors wish to thank the Berkeley Microfabrication Laboratory for providing an outstanding environment for process development and prototyping. Funding for the DM was supported in part by: 1) the National Science Foundation (NSF) Science and Technology Center for Adaptive Optics (CfAO), managed by the University of California at Santa Cruz under cooperative agreement AST 98-76783; 2) the National Eye Institute, 5R44EY015381-03 ; 3) the USAF, FA8650-04-M-6518, 4) NASA, NNG07CA06C, NNX09CE01P, and 5) the NSF, DMI-0522321.

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