2.6 MEMS CARE AND OPERATION

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1 Introduction

MagAO-X will use a micro-electro-mechanical systems (MEMS) deformable mirror (DM) from Boston Micromachines Corporation (BMC) for high-order wavefront correction. We have experience handling and controlling MEMS DMs from the Center for Adaptive Optics (CfAO) Laboratory for Adaptive Optics (LAO), from the "Villages" on-sky AO testbed at Lick Observatory's 1-m "Nickel" telescope, from the Gemini Planet Imager (GPI), and from the Subaru Coronagraphic Extreme AO (SCExAO) testbed and instrument. Here we present our plan for MEMS operation and safety of the equipment during development, deployment, and operations of MagAO-X.

Much of this document is based on KMM's version of a "MEMS handbook", entitled *MEMS practice, from the lab to the telescope* by Morzinski et al. (Photonics West invited paper, Proc. SPIE, 2012).

2 Lab testing

2.1 Verification of the MEMS: Upon receipt of the MEMS device from BMC, we will conduct a visual inspection of the surface, wire traces, and pins on the back. We will then carefully insert the MEMS in the ZIF socket while wearing an anti-static strap. After ensuring that the maximum voltage is limited in hardware on the electronics to the BMC-specified value, we will power on the control electronics. Here we assume that BMC will specify the max voltage as 300 V, but the exact value will be determined upon receipt.

MEMS devices are controlled via a voltage applied to a capacitor which pulls the actuator down; there is no inverse "push" motion, so the device is operated at a bias voltage to allow for displacement in both directions. The bias is determined by lab testing to discover which voltage is in the mid-displacement range for the majority of the actuators. MEMS have limited stroke so selection of the bias voltage is important to maximize the stroke in both directions (Fig. 1). Furthermore, because MEMS devices have a stiff and broad influence function (Fig. 2), the best choice of bias voltage varies based on whether a single actuator is being poked or a larger region of actuators are being displaced. To start with, we will extrapolate the best bias voltages for lower-powered previous LAO generation MEMS devices, as seen in Tab. 1.

Table 1: Suggested bias voltages for single-actuator and full-device displacement.

Maximum voltage	Mid-displacement voltage (single actuator)	Mid-displacement voltage (3x3 region)
160	110	90
200	140	120
225	160	140
$\sim$300*	$\sim$210*	$\sim$190*

* Maximum voltage to-be-determined (T.B.D.) as specified by BMC.
* Bias voltage T.B.D. for 300-V bias based on lab testing.

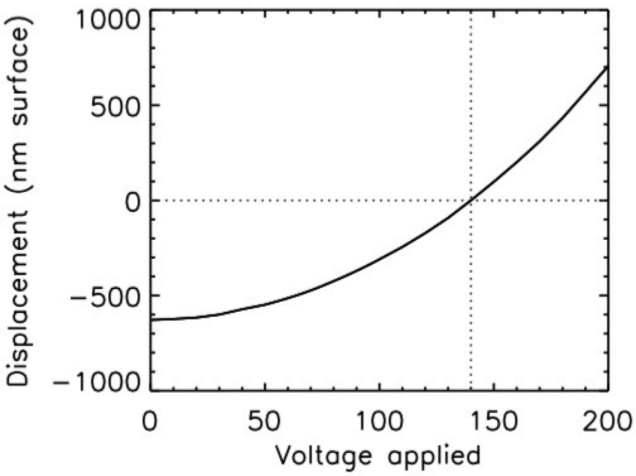


Figure 1: Displacement vs. applied voltage, 1 actuator (Villages MEMS).

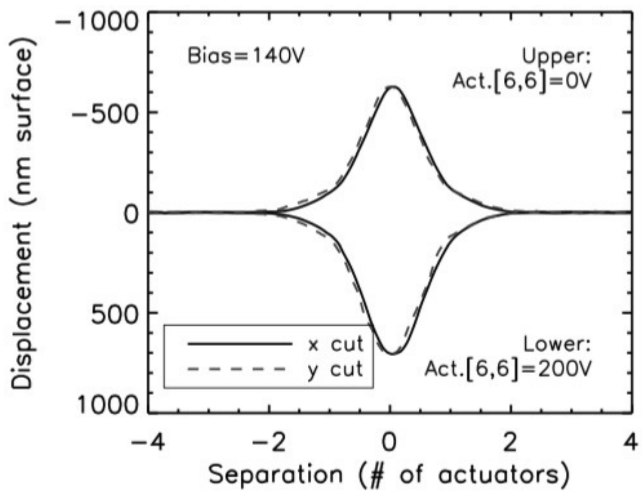


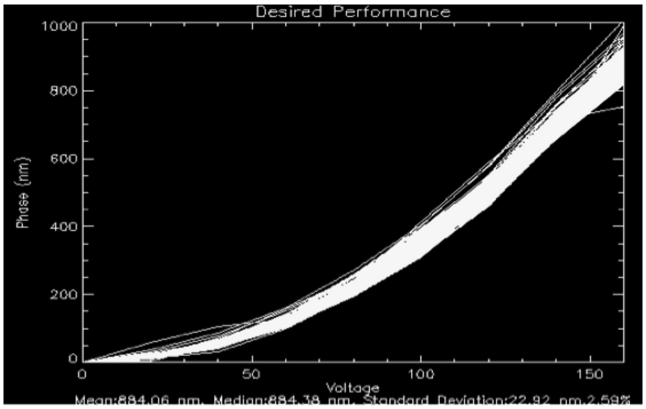
Figure 2: Influence function, 1 actuator (Villages MEMS).

We will apply a uniform bias voltage to the MEMS (∼190 V) and take an image with our Zygo interferometer. We will also take an image at 0V and at the maximum voltage (∼300 V). These images give us the un-powered shape, test the basic electronics and control, and identify "dead" actuators that do not move as identified by subtracting the 0 V and 300 V images. The next step will be to verify the mapping of the actuators and begin to test their response to voltage. We will carry out the LAO-standard "rows-and-columns" test where we apply ∼300 V to each row and then each column, sequentially, while the rest of the device is at a bias voltage of ∼210 V. We will measure the surface with the Zygo interferometer in the lab, which is aligned to achieve a spatial resolution of ∼20 pixels across each actuator. The Zygo images will be inspected to find mis-mapped rows or columns.

2.2 Actuator characterization: Actuator funtionality will be characterized in detail by measuring the displacement as a function of voltage for each actuator. To characterize each actuator, we will step up the voltage on each actuator individually from 0 to 300 V in steps of 30 V and take a Zygo image at each step. Because the influence function falls to zero at a spacing of a couple actuators (precise value T.B.D. in the lab), each actuator can be measured independently by applying a voltage to every 4th actuator across a row and down a column.

Irregular actuators can be non-responsive ("dead"), under- or over-responsive, coupled to a neighbor ("floating"), or responsive only to the level of the bias. In 2005 CfAO summer student Layra Reza did a thorough characterization of the zoology of actuator failures. She found that in 2005, a 1024-actuator BMC device had 96.2% well-functioning actuators. Of the remaining 3.8% irregular actuators, 78% were coupled pairs. The other irregular actuators included under- or over-responsive actuators (not a quadratic displacement curve), or actuators that moved up to the bias and then stopped. Her results are shown in Figs. 3 and 4. We have contracted with BMC for a device free of actuator irregularities within the clear pupil; the actuator characterization test will be important to investigate the functionality of each individual actuator.

2.3 Calibrating the MEMS: To shape the wavefront, the MEMS must be calibrated for its voltage response. The influence function is the displacement of the entire MEMS surface when a voltage is applied to a single actuator. Because the MEMS has a stiff continuous facesheet, the neighboring actuators are displaced somewhat as well. Figure 2 shows the influence function of the 144-MEMS used in Villages. The single actuator influence function



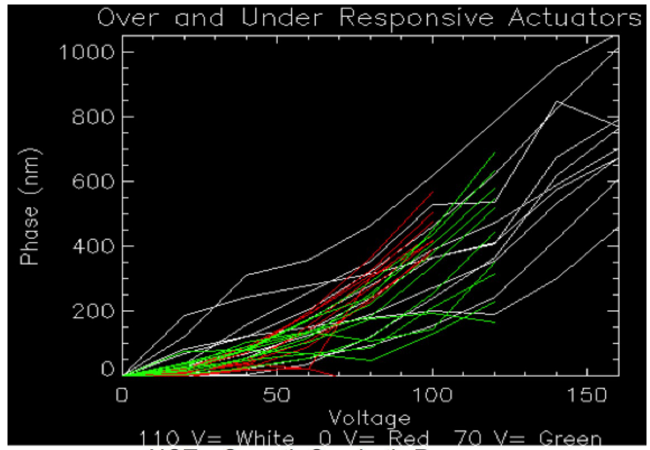
Mean - 884.06 nm

Standard Deviation

22.92 nm or **2.59 %**

96.2 % of All tested actuators constitute these results.

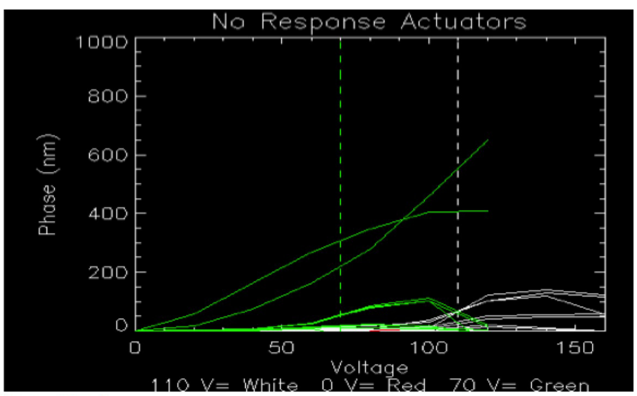
Desired performance: These actuators have quadratic displacement curves.



NOT a Smooth Quadratic Response

1.1 % of Actuators

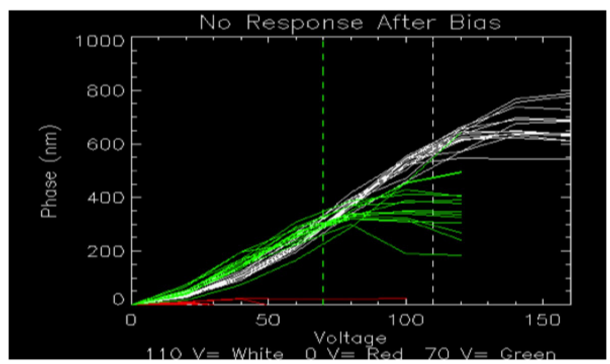
These irregular actuators are over- or under-responsive.



Float with Bias

- Problem with Electronics (Digital-to Analog-Converter)
- MEMS Short Circuit 1.1 % of Actuators
- Variability

These actuators are not "dead" but float with their neighbors.



Actuators do not move beyond the surface level

- Does the Bias determine the maximum voltage?
- Mechanical Problem 1.6 % of actuators

These actuators do not move above the surface level.

Figure 3: The zoology of good and bad BMC MEMS actuators as characterized by CfAO summer student Layra Reza (2005). This was an early-generation device and BMC's yield improved over time, from 97.9% to 99.5% in 2005–2012 for the old 1k-MEMS devices. We will conduct the same tests to measure the individual displacement curve of each actuator on the MagAO-X MEMS. This will both identify irregular actuators as well as calibrate the displacement curve for use in closed-loop control.

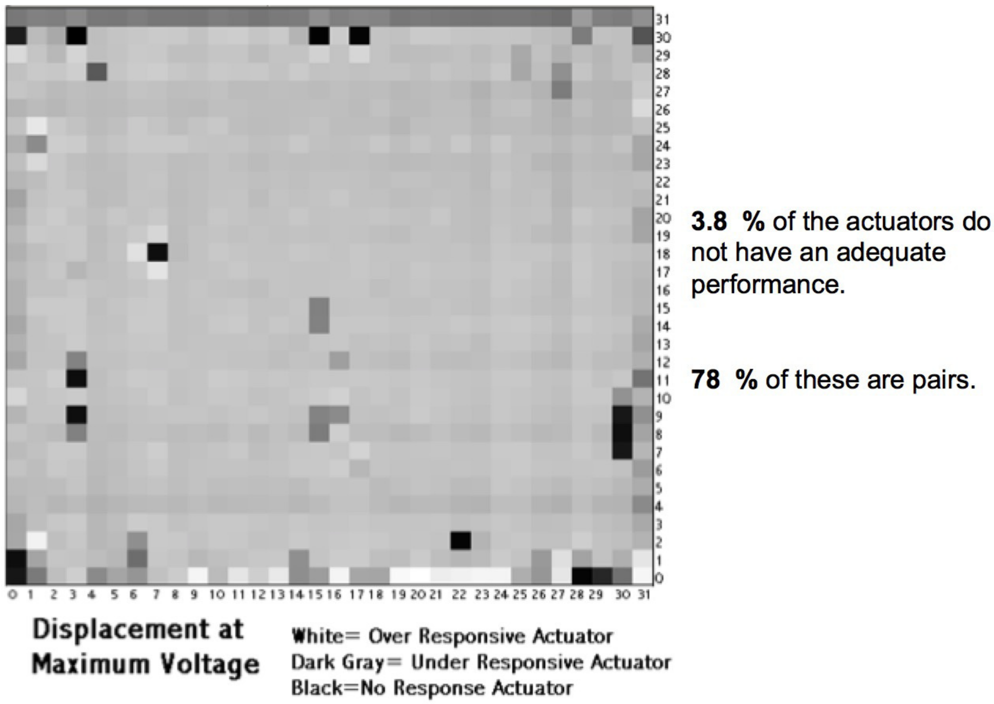


Figure 4: Results of a 2005 test on a 1024-actuator BMC MEMS DM for actuator functionality. We will similarly test each actuator of the MagAO-X MEMS to verify receipt of a device free of actuator irregularities within the clear pupil.

for a 1k-MEMS falls to 26% at one actuator distance and 4% at two actuators distance, and is uniform with varying bias voltage and applied voltage. This will be measured in the lab with the Zygo for the MagAO-X MEMS.

The displacement as a function of voltage is needed for applying shapes. The voltage that gives the displacement in the middle of the range is used as the bias. Figure 1 shows the single-actuator displacement curve for the 144-actuator Villages MEMS. Stroke has improved with advanced designs, after trading with facesheet thickness, surface curvature, and actuator spacing. See previous document for our MEMS specifications.

When calibrating the voltage-displacement curve (recall Fig. 1), in the LAO we would usually test only four actuators, fit a quadratic, and take the average curve for the entire device. However, if one takes the time to calibrate all actuators individually, there is an effect. Fully-functional actuators show a 23% variation in their displacement curves. This effect would account for 2030 nm rms wavefront error in an open-loop control model using an average rather than individual voltage-displacement curve for each actuator. Furthermore, closed-loop performance can be tweaked with an individual voltage-displacement curve for each actuator. Thus for MagAO-X it may be worthwhile to individually calibrate the voltage-displacement curve of each actuator, which we will do in the lab with the Zygo.

3 Care and Handling

There are two common failure mechanisms for MEMS actuators: snap down and humidity damage. In a snap-down failure the actuator has had too much voltage applied and the electrostatic force overcomes the restoring spring force and the actuator gets stuck in the highest-volt position. It is possible but not recommended that snapped down actuators can be freed by poking them with a probe. Snap-down is prevented with hardware and software safety stops to the maximum voltage that can be applied.

3.1 Power: At the LAO we had a device early on in testing on which we often left the same 4 actuators (used for alignment) strongly poked in the maximum voltage position with the rest of the device at a lower bias, on occasion for hours to days at a time. Over time these actuators did not return completely to the zero-volts position, but bumped slightly when unpowered. This cause still remains unknown, but the actuators remain functional. We modified our habits to unpower the device when not in use, and this has not been a problem with subsequent devices. At MagAO-X we will leave the MEMS powered off when not in use.

3.2 Humidity Safety: Voltage in the presence of humidity can induce dissociation of water, causing anodic oxidation of poly-silicon. Water dissociates into OH and H^+; the negatively-charged OH ions are attracted to the positive anode, where they react with the poly-silicon to form non-conducting SiOH and SiO_2, also known as glass. Over time with a combination of high voltage and high humidity, the connections for the actuators oxidize and the actuator gets stuck in the zero-volts position. It is possible that if there is oxidation on the device it would be visible under a microscope. Here we describe how we will protect the MEMS from humidity damage.

The deformable mirror must only have high voltage applied to it in low humidity conditions ($<$20%). The chamber around the deformable mirror is not perfectly sealed; a dry atmosphere could not be maintained in the chamber in a static fashion (drying it out and sealing it). Instead, dry air should be flowed through the deformable mirror chamber constantly. Figure 5 illustrates the set-up for SCExAO.

Air from an oil-free compressor is passed through a desiccant to dry it before entering the gas monitoring system. The gas will typically arrive from the compressor at a pressure of 60-100 psi. To ensure the deformable mirror is not damaged by over pressure, a low-pressure regulator will be used which limits the maximum output pressure to 1.4 psi above ambient. A flow regulator will be used to restrict the flow to a dribble. After the regulator a pressure sensor and a pressure relief valve will be used to monitor the pressure and ensure that an overpressure cannot occur (doubly redundant with the regulators). The gas will be sent to the DM and the humidity of the gas returning from the DM will be monitored upon return.

A vacuum pump will be connected to the end of the line to (1) reduce the pressure in the chamber to about 80 Torr and (2) pull the dry air through the chamber to ensure that wetter air that leaks in through the joints does not raise the humidity in the chamber. 80 Torr is required to remove the damping effect of the air in the chamber and allow for the deformable membrane to be modulated at its maximum speed. Going below this significantly (down to 10-20 Torr) could result in electric breakdown and permanent damage. A Venturi pump could easily be used that is driven by the same compressed air line.

An interlock based on both the pressure and humidity will be used to switch the electronics to the deformable mirror off in case the pressure gets below 80 Torr, or the humidity gets above 20%. An software interlock will also be established which reduces the signal set to the deformable mirror to 0 in case nothing has been applied for the last hour. This is to prevent someone leaving something on the deformable mirror, going home and finding out the various interlocks failed.

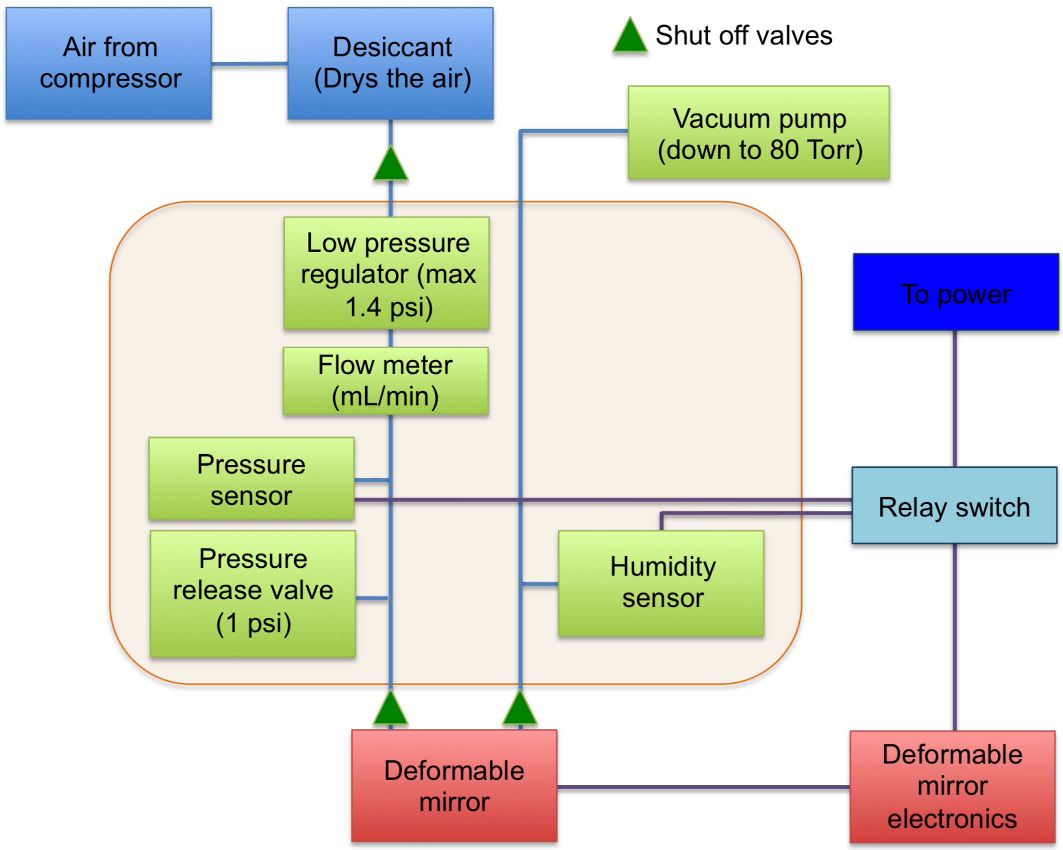


Figure 5: Keeping the MEMS dry at SCExAO. We will use the same set-up for the MagAO-X MEMS to continuously flow dry air through the pseudo-hermetically-sealed MEMS window to ensure the poly-silicon is protected from humidity damage.