

# Advanced Curvature Deformable Mirrors

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## ABSTRACT

The need for a variety of deformable mirrors (DMs) is growing steadily as more applications are brought on line, components are more widely available and adaptive control evolves into an off-the-shelf item. While the bulk of the readily available systems are of the push-pull variety, curvature mirrors have much to offer in simplicity and efficiency. We will explore paths for development of these components.

## I. Introduction

Adaptive correction systems are in use in a number of applications and planned for many more. Multi-conjugate and multi-object systems use multiple fairly normal correctors while extreme-AO applications require high-order DMs. Typically, any component becomes difficult to fabricate when it becomes too small, too large or too functionally dense like high order systems. Larger telescopes, for example, drive towards larger DMs to avoid pupil mapping and field of view effects but dynamic range and inter-actuator motion requirements become more challenging. Given the breadth of the ways in which AO is useful, it is valuable exercise to add to the catalog of components applicable to the problem.

Functionally, curvature AO systems look like any other closed loop control systems but the wave front sensor (WFS) and deformable mirror (DM) implementations are unique to curvature AO. Either the WFS or DM can be used separately but it is in their combination that many new advantages emerge. Curvature AO has been under development at the IfA for more than a decade [1] and is in use at the CFHT, the Subaru telescope and in the Southern hemisphere at ESO. We refer to traditional AO systems based on slope-sensing wave front sensors combined with push-pull deformable mirrors as Shack-Hartmann or **SH** type and to systems that combine curvature sensing and correction as Roddier-Curvature or **RC** type. The RC WFS works by differencing intra- and extra-focal images. The information contained in the difference image is sufficient for the DM to reconstruct the wave front. The sensitivity of the WFS can be tuned by changing how far out of focus the images are obtained.

## II. Curvature Adaptive Systems

The basic curvature DM (Figures 1-3) is a sandwich of piezoelectric material poled through the thickness. Using photolithography, we apply an electrode distribution on one side and a reflective working pupil area on the other. When we apply voltage to an electrode, it creates a local electric field through the thickness of the disk and the transverse piezoelectric effect causes the activated electrode to expand or contract in area. Since this action is applied either to a single element of the sandwich (unimorph) or oppositely to both elements of the system (bimorph) the net effect is to cause the disk to curve over the actuated region. The action of any given actuator of the DM changes the surface height everywhere but since the WFS only sees the DM in curvature, the action looks local and the control matrix is consequently nearly diagonal. The long actuators at the outer edge of the deformable mirror are largely outside the working pupil so their action is to create a slope at the edge of the working pupil, exactly the quantity measured by the WFS.

When actuated with the DM with the control voltages derived from the WFS readings it takes on the curvature and edge slope distribution measured by the WFS. This information, together with the mechanical integrity of the DM is sufficient for the DM to reconstruct the input wave front error. In a curvature AO system there is never a formal reconstruction of the wave front either explicitly or implicitly in the control matrix. The WFS-DM combination is acting like an analog computer for wave front reconstruction. Consequently, although

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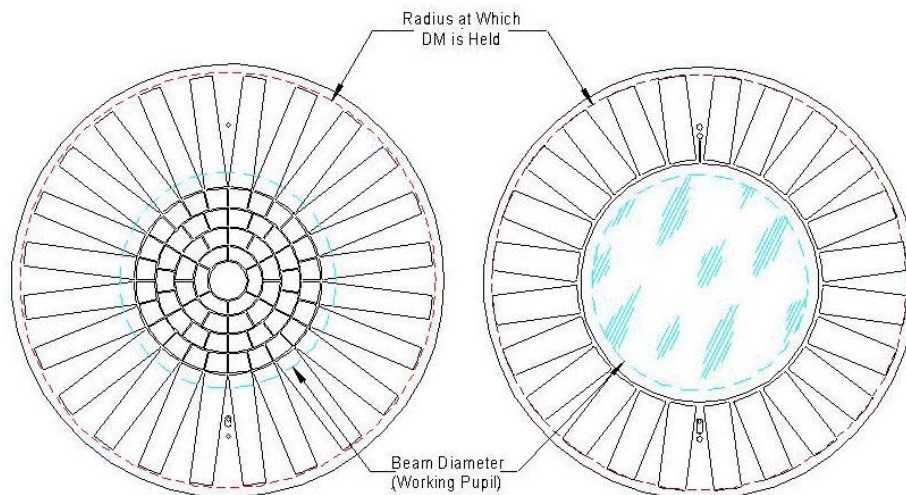
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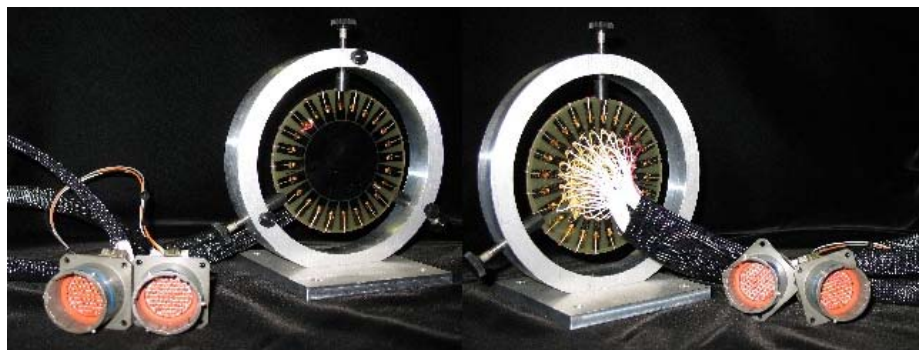
only local curvature is measured and applied to the DM, the whole wave front is reconstructed and the local wave front slope and phase must also be correctly reproduced. In summary, for an RC AO system:

- Interaction and control matrices are nearly diagonal because the WFS measures exactly what the DM action creates
- The sensitivity of the WFS to different curvature scales is tunable in real time as atmospheric conditions change.
- No formal wave front reconstruction is required.
- Each channel corrects local phase, tip-tilt and focus (curvature) although only curvature or slope is measured.

In implementing RC systems, the challenge is to exploit these features. Since each curvature channel corrects so many modes, fewer channels are needed for a fixed level of correction. Since only one sensing element per channel is required, an RC WFS needs fewer detector elements than the equivalent SH system. This allows building an RC WFS with photon counting avalanche photo diodes (APD) on each sensing channel. Fewer channels and photon counting on each channel truly optimize RC system for low light operation. Add to this the sparse, nearly diagonal control matrix and no need for a formal reconstruction and we can see that RC systems are also optimized for speed.



**Figure 1. Back (left) and Front (right) actuator patterns of our 85-element deformable mirror. The smaller curvature actuators are applied only to one side and operate in a unimorph mode. The long edge actuators are on both sides operate as a cooperative bimorph essentially doubling the curvature that can be achieved**



**Figure 2 Front(left) and back (right) views of a completed DM. The mount shown is a 3-point lab test cell. In practice the DM is captured between two o-rings which constrain it over its entire circumference.**

### III. Curvature Adaptive Mirrors

The RMS focus error we expect in a turbulent atmosphere decreases as the size of the region under consideration decreases but the geometric curvature increases as the size of the region decreases. It is harder for curvature mirrors to bend enough to match the curvature of atmospheric wave fronts as the actuator size decreases.

Thus minimum surface radius of curvature ( $R_{\min}$ ) is a performance limiting parameter.  $R_{\min}$  is a local property of the DM in that it is essentially independent of the boundary conditions and is given by:

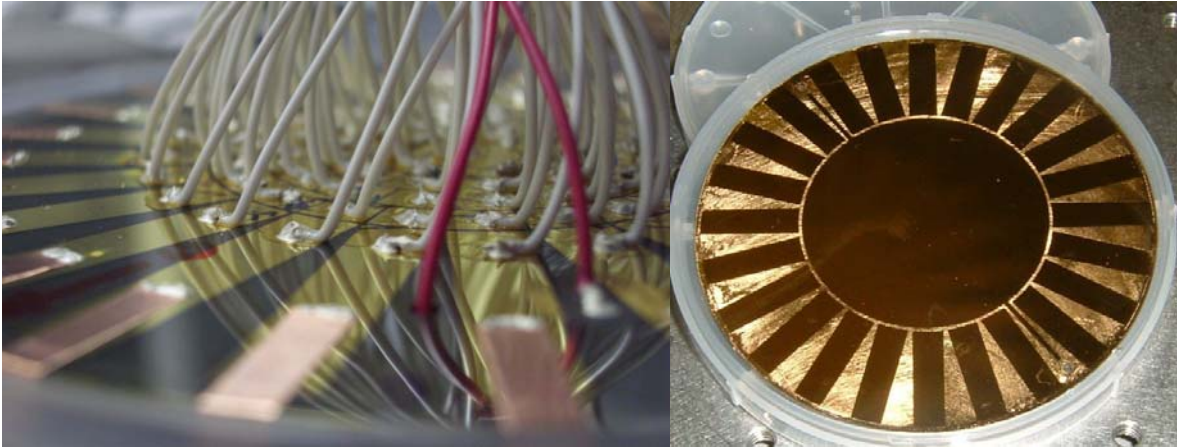
$$R_{\min} = \left( \frac{t}{S_{\max}} \right) \\ = \frac{1}{d_{31}} \left( \frac{t}{E_{\max}} \right)$$

The quantity  $S_{\max} = d_{31} E_{\max}$  is the maximum strain created in the material.  $E_{\max}$  is the maximum, useful electric field created in the material and is limited by the material's coercive field, is the field at which the residual polarization of the PZT begins to reverse.

These types of mirrors are constrained only at their edges so the resonant frequency  $f_o$ , is also a critical parameter. For a simple homogeneous disk of thickness  $t$  fixed at radius  $D / 2$ , the resonant frequency is:

$$f_o \propto \frac{t}{D^2}$$

where the constant of proportionality depends on the physical parameters of the piezoelectric material used.

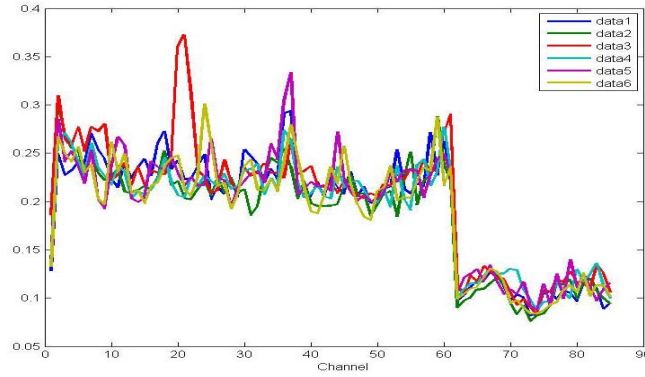


**Figure 3(Left)** A back of a completed deformable mirror with the electrode pattern and wires applied. **(Right)** The front face of an in-process DM prior to the Gold lift-off process. The wafer is 100mm in diameter and 2mm thick and the working pupil is 50mm in diameter. The central electrode is the base coat for the reflecting surface and also serves as a focus electrode to help flatten the DM. We have developed the ability to polish the bulk material to a surface roughness of 35Å so no additional replication step is needed. In use the DM is supported at its outer edge.

The two equations above frame the essential trade-off in designing a curvature DM. Making the DM thinner allows it to curve more, but a thinner DM has a lower resonant frequency. Increasing  $R_{\min}$  means the fraction of time the DM will saturate increases. The required curvature will also depend on the pupil mapping ratio. For a homogeneous design we have shown [2] that scaling the DM so that the resonant frequency remains constant will keep the ratio of the limiting curvature to the required curvature a constant.

There is only one free parameter for a homogeneous design and that is the ratio of the total DM diameter to the working pupil diameter. Traditionally this has been set at a factor of 2. The plot below shows the RMS

correction voltage taken from AO captures from the Gemini South Near-Infrared Coronagraphic Imager (NICI) that uses a DM virtually identical to the one shown above. The bimorph edge benders (Channels 62-85) require significantly less voltage to operate even though the NICI DM is held at a diameter of 90mm or 1.8 times its 50mm pupil diameter. The resonant frequency is higher (1KHz vs 670Hz) than earlier versions and it appears that the outer diameter could be reduced even further.



**Figure 4.** Using a Bimorph configuration for the edge benders significantly reduces the correction voltage they require. Capture data from NICI shows that the typical voltage applied to the curvature actuators is more than twice that applied to the edge benders. This margin can be used to reduce the diameter at which the DM is held, increasing the resonant frequency

#### IV. A Simple Approach to Higher Order Deformable Mirrors

Given that there is just one free parameter in a homogeneous design as long as the material properties remain fixed, it is essential to explore the performance gains available from varying it. To move towards higher order designs we have the following recipe:

1. Reduce the overall diameter of the DM by a factor  $\alpha$ . This increases the resonant frequency by a factor of  $\alpha^{-2}$ .
2. Thin the DM by a factor of  $\alpha^2$ . This decreases the resonant frequency back to its initial value but decreases  $R_{\min}$  by a factor of  $\alpha^2$ .
3. Reduce the applied voltage by a factor of  $\alpha^2$  to keep the electric field below the coercive field.

This process results in a thinner DM that can bend to a tighter radius for the same resonant frequency. It is limited by at least one theoretical factor: The DM radius cannot be reduced to the pupil radius since the fixed edge boundary condition is not valid at the pupil edge. For the current design, this implies a limiting radius of curvature that is  $\frac{1}{4}$  of the nominal value operating at  $\frac{1}{4}$  of the current operating voltage. A separate tip-tilt correction could reduce the edge bending requirements somewhat but the edge bender voltage is mostly driven by local slope correction.

In addition to the limit set by the pupil radius, a practical problem also arises by the need to thin the DM to relatively small values. For a DM which is 70% of the current one the required total thickness is 1mm, half that of the current DM. We set up an experiment to pursue this idea. Since the overall diameter of the DM is to be limited we started with 86mm diameter wafers. We found that the wafers could be thinned, lapped and polished to thicknesses well below 1mm. The image below shows a wafer that started as two 2mm thick pieces of material and ended as a single 0.7mm thick bimorph sandwich. This wafer would have  $R_{\min} = 4 - 5$  meters, sufficient for 400-500 actuators on an eight meter telescope working in one arc second seeing.

#### V. Composite Deformable Mirrors

Homogeneous deformable mirrors naturally avoid CTE problems but there are several reasons to abandon this simplification:

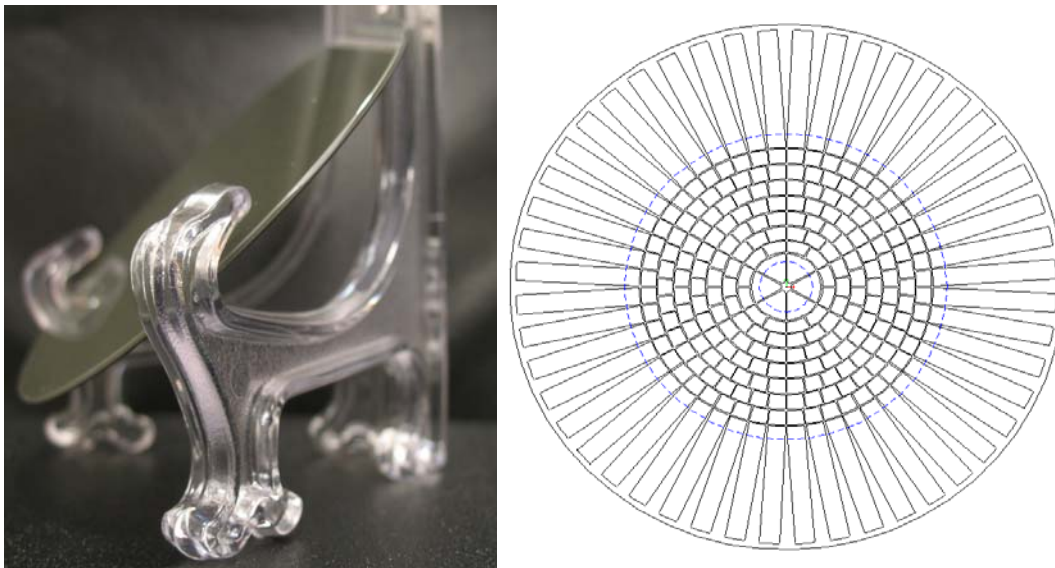


1. Piezoelectric materials, particularly of the high density type that can be polished, do not come in very large pieces.
2. PZT is very dense so parts of the DM that are not active “dead weight” and just decrease the resonant frequency.
3. Polishing to an optical surface takes a long time and is the chief cost element making these types of DMs.

For a composite DM we start with an optical quality face sheet or one that can easily be brought to such a state and then build the active part on the back by bonding curvature actuators to it. To illustrate the motivation for this approach the table below compares the basic DM homogeneous design with composite designs using just a glass wafer and a wafer of Carbon Fiber Reinforced Polymer (CFRP). In both cases minimum bend radius decreases and the resonant frequency increases.

	Radius of Curvature	Lowest Mode
Homogeneous – PZT	10.7m	670 Hz
Asymmetric – Glass	9.2m	815 Hz
Asymmetric – CFRP	8m	733 Hz

In order to accommodate the use of dissimilar materials it is now necessary to match the CTE of the face sheet to that of the PZT. The effects of a mismatch are primarily focus and can be fixed by the system itself but it would reduce the dynamic range available for correction. Since the maximum strain created in the DM is of order  $10^{-4}$  it is reasonable to assign 10% of this to thermal effects. Assuming a 20 degree operating range around room temperature gives a permissible CTE mismatch of order 1ppm/C. We have undertaken experiments to measure and confirm the CTE of the materials we use and to build composite mirrors based on this idea. It appears that several available glasses would meet the CTE match requirements. A real benefit of this approach is that it allows the use of new materials like CFRP whose thermal and mechanical properties can be very finely tuned.



**Figure 5(Left) An 86mm wafer thinned to 0.7mm thick with a minimum bend radius of order 5m. (Right) Design for a 264 element deformable mirror to be built on these wafers.**

## **VI. Conclusions**

- I. There are several approaches to building the kinds of deformable mirrors needed for future applications.
- II. Larger curvature deformable mirrors can be built on a face sheet with actuators constructed on its back.
- III. Such composite DMs allow the use of new materials whose properties can be very finely tuned.
- IV. Higher order mirrors can be made with current technology by careful design of the electrode pattern and processes we have developed for lapping PZT.
- V.

## **References**

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- [2] Q. Yang, C. Ftaclas, and M. Chun. Wavefront correction with high-order curvature adaptive optics systems. *Journal of the Optical Society of America A*, **23**:1375–1381, June 2006.