Piezoelectric Microactuator Technologies for Wavefront Correction in Space

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ABSTRACT

There is a need for ever-larger apertures for use in space based optical imaging systems. Requirements on optical instrumentation for future observations in space will place rigorous demands on wavefront quality. The design of such mirrors involves a balance between the utilization of ultra-lightweight mirror and support structures, and the active correction of the increased deformations due to these compromises in structural rigidity. Performing wavefront control with a primary mirror requires precision and stability over a large structure. The wavefront correction, therefore, can be partitioned in spatial frequency between the primary mirror and a tertiary deformable mirror (DM). To realize the full potential of new ultra-lightweight, active primary mirror, the large-stroke microactuator and DM technologies need to be developed. This paper presents a set of candidate components: linear microactuator technology and a piezoelectric unimorph-based large-stroke DM technology, in the context of a lightweight active mirror concept.

INTRODUCTION

The application of extremely large (> 30 m), lightweight (< 1 kg/m²) apertures to space-based imaging will enable substantial performance gains for future space missions. However, the manufacture and launch of rigid, monolithic apertures of such dimensions would be prohibitively expensive. Practical ultra-large, ultra-lightweight aperture systems will more likely be either segmented or flexible monolithic primary mirrors whose large surface errors are corrected by active and adaptive wavefront controls [1]. Current state-of-the-art deployable aperture technologies include inflatable structures using flexible polymeric membranes [2] and nanolaminate-based rigid-shell mirrors [3], which uses electroactive polymer actuator pieces bonded to the back side of a nanolaminate shell to achieve curvature correction.

While mirror facesheet technology development has resulted in significant advances in lightweight optical quality facesheet materials, to date no comparable development has occurred in actuator technology development. The available actuators are still relatively heavy and bulky. Using ultra-lightweight microactuators, the ultra-large mirror system can be designed to have very low areal density. For instance, extremely thin nanolaminate mirrors (with an areal density of < 0.2 kg/m² [1]) can be supported by flexure beams and microactuators to meet the areal density requirements of future space telescope mirrors. An important requirement of the microactuators is the normally-latched actuation mode or zero-power latching scheme. Here, the zero-power latching refers to a capability that a moving part remains passively gripped at the same position when power (i.e. voltage) is off. The primary benefits of latching are power efficiency and robustness against power interruption. Other generic requirements for ‘shape correction’ of mirrors include a stroke of >1 mm and a step resolution of <30 nm with the actuation force of a few tens of mN. Current conventional piezoelectric linear actuators are too large and massive for the application in ultra-lightweight space telescopes. Several MEMS-based linear actuators have been previously reported; however, none appear to satisfy all the requirements stated above. For example, A MEMS-based electrostatic linear motor previously reported [4] only moves 400 µm stroke, while another actuation design uses thermo-elastic links, [5] a thermal actuation mechanism undesirable for our applications. This is because thermally actuated devices suffer the risk of random actuation if ambient heating or cooling occurs, resulting in uncontrolled initiation of the actuation.
mechanism. A surface micromachined stepping actuator [6] offers 500 µN force, +/-100 µm travel and 10 nm step size, but the actuation force of a few tens of mN is required with a larger actuator stroke. Linear actuators using electrostatic clutching have been reported [7, 8]. However, to our knowledge, none of the previous MEMS linear microactuators has demonstrated zero-power latching capability. Therefore, the need for development of a new actuation mechanism is vital to provide both large-stroke and relatively large-force actuation using a small and lightweight actuator.

On the other hand, performing wavefront control with an actuated primary mirror alone is still very challenging, since the required precision and stability over a large structure may not be accomplished using the actuators alone. Requirements on optical instrumentation for future astronomical observations in space will place rigorous demands on wavefront quality. Therefore, the wavefront correction can be partitioned in spatial frequency between the primary mirror and a tertiary DM as shown in Figure 1. In this scheme, low-spatial frequency errors can be removed by the coarsely actuated primary mirror using microactuators, while high-spatial frequency errors can be removed by the large-stroke, high-density DMs. For these DMs, large-stroke actuators will be needed on the primary mirror in order to form an image. For many of the applications, the availability of high-performance DMs will play a critical enabling role. Given the variety of applications relevant to space operations, one sees there is no single ideal DM architecture. Electrostrictive lead magnesium niobate (PMN) actuators have achieved a surface stability of 1 angstrom and a surface figure of λ/20. However, although these technologies are in widespread use, they have only limited actuator stroke (approximately 0.5 μm stroke at 1/mm² actuator density, for PMN-based mirrors). Micromachined continuous membrane DMs have been fabricated [9-13]; however, such devices are based on electrostatic actuation, and consequently have limited mirror stroke (~2 μm). Currently, the large-aperture technology development being pursued under the Gossamer program has yet to demonstrate the potential for diffraction-limited wavefront quality over large apertures. These problems are overcome in the DM technology, which simultaneously meets the requirements of scalability and stroke, based on large-stroke actuators mated with a flexible mirror facesheet. The unique approach of combining PZT unimorph actuator technology with membrane transfer technology [14] can provide flexible capabilities in fabricating DM structures to correct the large wavefront errors associated with space-based telescope apertures.

This paper discusses the actuator component technologies including linear microactuators and DMs that can be incorporated into the AO system concept for future space telescopes. In addition, the modeling on a pathfinder lattice structure is discussed, simulating an actively controlled ultra-large aperture. A detailed analysis of the integrated performance of these components and their performance predictions at the telescope level is a part of future research and development work.

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Figure 1. Adaptive Optics (AO) system equipped with a DM for a space-based, earth-observing ultra-large telescope: Wavefront errors are caused by atmospheric turbulence and by primary mirror imperfections due to deployment, thermal loading, and mechanical jitter. Low-spatial frequency errors can be removed by the coarsely actuated primary mirror using microactuators. The AO system operates by determining the shape of the distorted wavefront, and using a DM to restore the uniform wavefront by applying an opposite, canceling correction.
LINEAR MICROACTUATOR

When the wavefront correction can be partitioned in spatial frequency between the primary mirror and a tertiary DM, linear microactuators are used to coarsely actuate the primary mirror to remove low-spatial frequency errors. In this section, we present our demonstration of a normally-latched linear microactuator. This actuator is ultimately capable of large-stroke and high-precision motion. The actuator in this paper has a single degree of freedom, which can be located and oriented in any desired direction in the future telescope mirror structures in space.

DESIGN AND ACTUATION PRINCIPLE

Figure 2 shows the schematic of the linear actuator, consisting of a slider and two comb drive units mounted on a rail substrate [15]. The slider is inserted at the center trench and grasped by clutches. The actuator is driven by a combination of the electrostatic comb drive and the laterally placed PZT actuator. Figure 3 illustrates operation sequence of the actuator. Step (0) shows initial un-powered status. In step (1), comb drive unit A is released by powering the comb drive while the unit B remains clutched. In step (2), the unit B and the slider is laterally pulled towards the right by a PZT stack actuator. In step (3), the unit A is clutched while the unit B is released. In step (4), the unit B is pushed back by the PZT. One cycle of actuation yields one step increment of the slider motion toward right. By repeating the actuation sequence for many times, large cumulative stroke is achieved. This sequence is reversible; therefore, the slider can be driven bidirectionally. The step increment resolution can be adjusted by controlling the voltage applied to the PZT stack. The intertwining U-letter shaped comb drive unit design is intended to enhance stability of the slider motion. During the operation cycle, the slider is gripped by at least four clutches at a time; also, the slider is confined to linear motions only, mitigating undesired slider tilt and drag friction. This actuator is capable of zero power latching; that is, the slider is gripped and its position is maintained when power is turned off.

The comb drive unit is fabricated on a SOI wafer with a 100-µm-thick device layer to increase both the stiffness and the electrostatic force. For processing this 100-µm-thick layer, the aspect ratio limitation in the Deep Reactive Ion

Figure 2: Actuator schematic. The actuator is driven by a combination of the electrostatic comb drive and PZT actuators.

Figure 3: Operation sequence. (0) Unpowered latching mode, (1) Unit A released, (2) Unit B laterally moved to right, (3) Unit A clutched, Unit B released, (4) Unit B move back.
Etching (DRIE) process confines the trench width (comb gap) to be larger than roughly 5 μm. Therefore, the comb drive structure is fabricated as “unengaged” so that the initial gap between each comb tooth is a 5 μm gap. The slider insertion allows the comb drive teeth to get post-engaged, thereby narrowing the comb-tooth-gap to approximately 1 μm. Once the slider is inserted, tethers are displaced by approximately 10 μm and, therefore, grip the slider without external power since they are pre-stressed. By applying voltage to the comb drive, the clutches are electrostatically pulled away to release the slider. The estimated bending force applied to the tethers -approximately 20 mN- as a clutch is displaced by 10 μm during the slider insertion process and bends the tether beam. On the other hand, the repulsion of the 10-μm wide tether beam perpetually pushes the slider with the force of 20 mN. Before the slider insertion, the comb gap is approximately 5 μm and the electrostatic force is negligible. Once the slider is inserted, the comb gap narrows to approximately 1 μm and the electrostatic force is significantly increased. By applying 200 V to the comb drive, the estimated electrostatic force is approximately 40 mN, which exceeds the estimated tether bending force of 20 mN. Thus, the tethers are further bent by a few additional microns, so that the clutches are pulled away from the slider. Assuming the static friction coefficient is 0.2 [16], each clutch can grip the slider with a force of up to 4 mN. In the power-off latching mode, four clutches on one side grip the slider with the force of 16 mN. This force can be significantly increased by adjusting the device layer thickness and the number of comb drive columns and by surface coating on the slider to increase the friction coefficient.

**Fabrication and Characterization**

The linear actuator consists of two comb drive units, a slider, a rail substrate and a PZT-stack actuator. Individual parts were fabricated separately and manually assembled. The comb drive unit was made from a SOI wafer using DRIE on both sides of the wafer. To control the sidewall profile of the tether beams during the DRIE process, H-shaped etch fin geometry was employed [17]. A rail substrate was made by attaching side-rails to base plate by epoxy adhesive. The slider was fabricated by slicing silicon wafer using a dicing saw. Therefore, the sidewall surface of the slider is slightly striated at oblique angle. The surface of the slider was coated with a Plasma Enhanced Chemical Vapor Deposition (PECVD) dielectric film to minimize sticking of the silicon slider to the silicon clutches. After completing the fabrication of the actuator components, the driver units were mounted on the rail substrate. The slider was manually inserted between clutches using a probe needle. The striation of the slider sidewall seems to negatively impact the slider insertion yield due to nonuniform friction which sometimes overstressed tether beam springs. After the slider insertion, the tether beams are displaced by approximately 10 μm and the slider is clamped by the tether beams. Finally, PZT-stack actuator and a lid were attached using epoxy adhesive, and the assembled structure was wire-bonded. A side stopper was employed to limit the movement of comb teeth in order to prevent mechanical damage. The side stopper and the moving part of comb teeth were both electrically grounded to prevent pull-in contact and arc discharge. Figure 4 shows a fabricated linear actuator after the assembly and wire bonding.

![Figure 4: Image of a fabricated linear actuator after assembly and wire bonding.](image-url)
Before testing sequential operation, each comb drive unit was tested by applying voltages under a microscope. The comb drives started to pull the clutches away from the slider when a voltage exceeding 100 V was applied. The actuation test was performed with voltages equal to or less than 200 V applied to the comb drive. Sequential actuator operation was tested using a LabVIEW-based setup consisting of interfaced power relays and power supplies. The voltages applied to the comb drive and the PZT-stack actuators were 200 V and 20 V, respectively. The measured cumulative stroke after 200-cycle actuation is 178 µm, with an operation speed of approximately 1 cycle per second. While the measured displacement was mostly linear with respect to cycle counts, occasionally nonlinearities were observed (not shown in figures) presumably due to the nonuniform friction caused by the dicing striation on the slider sidewall surfaces. The step size was varied by adjusting the PZT-stack actuator voltage. The measured incremental step size is approximately 59 nm/cycle, with the PZT-stack actuator voltage of 5 V; 384 nm/cycle, with 10 V; and 856 nm/cycle, with 20 V, respectively. The step size showed a tendency to be disproportional at lower PZT voltages probably due to PZT-hysteresis and/or slider-drag.

PIEZOELECTRIC MEMS DEFORMABLE MIRROR

Performing wavefront control with an actuated primary mirror alone is still challenging due to the required precision and stability over a large structure. While the wavefront correction is partitioned in spatial frequency between the primary mirror and a tertiary DM, high-spatial frequency errors can be removed by the large-stroke, high-density DMs. For these DMs, large-stroke actuators will be needed on the primary mirror in order to form an image. The DM described in this paper comprises a continuous membrane mirror supported by an array of PZT unimorph actuators.

DESIGN AND ACTUATION PRINCIPLE

The unimorph actuation principle is illustrated in Figure 5. The actuation principle is as follows: an electric field applied perpendicular to the membrane-mounted PZT thin film induces a contraction in the lateral direction, converted by the membrane geometry to a large out-of-plane deflection. The vertical deflection acts on the mirror membrane that is mounted over the microactuator. Compared to the bulk piezoelectric or electrostrictive stack actuators widely employed in commercial DMs, thin films require far lower voltages and less power to produce the same mirror deflection. To avoid stress concentration which might induce cracking in the actuator, circular diaphragm elements were chosen. In order to optimize the geometry of the unimorph actuator structure, a mathematical model was developed using an energy minimization method [18]. In this model, the total energy of the unimorph membrane under deflection is calculated using a deflection profile predicted by thin plate deflection theory. Subsequently, the total energy, consisting of the elastic energy due to the bending of the membrane, the potential energy stored by the film stresses, and the work done by the piezoelectric actuation, is minimized with respect to a Lagrange multiplier. The energy minimization calculation was performed for both continuous and patterned piezoelectric films.

![Figure 5](image-url): Actuation principle of the piezoelectric unimorph actuator. An electric field applied perpendicular to the membrane-mounted piezoelectric thin film induces a contraction in the lateral direction, converted by the membrane geometry to a large out-of-plane deflection. The vertical deflection acts on the portion of the mirror membrane mounted over the microactuator.
A proof-of-concept DM structure was fabricated using typical unimorph actuators, and its actuation performance was characterized using the WYKO RST Plus Optical Profiler. For fabrication of the mirror membrane, we utilized the membrane transfer process to transfer the mirror membrane onto the fabricated actuator arrays [14]. The membrane transfer process is briefly described as follows: The mirror membrane transfer process involves transfer of the single-crystal silicon layer from the SOI wafer following the metallization, bonding, and etching processes. SOI carrier wafers were used for the fabrication of the single-crystal silicon mirror membrane. The thickness of the transferred membrane is determined by the thickness of the SOI top silicon layer. A 20-μm-thick single-crystal silicon mirror membrane was transferred onto the actuator wafer. The actuator wafer and the SOI carrier wafer were prepared. Cr/Pt/Au metal layers were deposited and patterned to form bonding pad arrays on both the carrier and actuator wafers. A 1-μm-thick In layer and a 100-angstrom thick Au layer were deposited and patterned on both the carrier and actuator wafers using a lift-off process. The SOI carrier wafer was subsequently bonded to the substrate wafer. The backside etching was conducted in a 25 wt % solution of tetramethylammonium hydroxide (TMAH) at 80°C until the buried oxide was exposed. A specially designed Teflon fixture was used to protect both the backside of the bonded substrate wafer as well as the bonded interface. The exposed oxide was removed by using 49% HF droplets. An SF6 plasma etch was incorporated, as necessary, to selectively etch the transferred membrane in order to release membrane structures.

Figure 6 contains photographs of a fabricated DM with a 20-μm-thick silicon membrane mirror (50 mm × 50 mm area) supported by 400 PZT unimorph actuators. A WYKO RST Plus Optical Profiler was used to analyze the deflections of the mirror and actuator membranes. The measured maximum mirror deflection at 30 V is approximately 1 μm. This deflection for a DM shows that the stroke of the mirror membrane is approximately 40% of the stroke of actuator alone. The measured influence function (inter-actuator coupling) was approximately 30%. The full-scale measurement (up and down) of the mirror and actuator combination was not performed due to a lack of reference area on the mirror membrane. Hence, the measurements on the mirror membrane were made in the ‘differential mode’ only [18]. The full scale optical measurement protocol as well as the software and driver electronics for a DM device has to be established in the future in order to fully characterize the DM performance. For the actuator alone, the measurements were made with respect to reference electrodes. The stroke reduction can be minimized by varying the mechanical compliance (by optimizing the PZT/actuator membrane/mirror membrane thickness ratio). The frequency responses for the unimorph actuator, with and without the mounted mirror membrane, were obtained using a laser-doppler vibrometer. The resonance frequency of a 2-mm-diameter, 2-μm-thick PZT/15-μm-thick silicon membrane, and 60% electrode actuator was measured at 63 kHz, which far exceeds the bandwidth requirement for most DMs (~1 kHz) [18]. The bandwidth of the DM in this paper far exceeds the bandwidth requirement for most DMs that are applicable to several space and Earth science missions being envisioned by NASA. The future development plan includes demonstration of the DM technology by (1) flattening the mirror under a Michelson interferometer setup, (2) measuring the gains of all actuators, (3) measuring the temporal frequency response of several actuators, and (4) measuring the influence function of all actuators.

We have designed, fabricated and optimized large-stroke PZT unimorph actuators, and we observed a significant increase in the deflection when the PZT film surrounding the actuator was removed. Three different unimorph...
actuator structures have been designed, fabricated, modeled, and tested. In Figure 7, Case A shows a schematic of a typical unimorph actuator previously developed. It consists of a patterned top electrode (Au) on top of a PZT layer. This stack was prepared on a bottom electrode (Pt) deposited on the silicon layer (membrane). The size of the top electrode and the thicknesses of the PZT and silicon layers were optimized based on the energy minimization approach. Case B shows a schematic of a unimorph actuator with a ‘patterned’ PZT layer. The size of the PZT pattern was optimized using the modeling method previously developed [18]. Case C presents a schematic of an actuator with patterned PZT and patterned silicon layers. The measured deflection for an optimized actuator is 5.7 µm at 20 V (for an actuator with 2.5 mm diameter, PZT/Si = 2 µm / 15 µm thick, PZT patterned over 60% of the membrane diameter, and silicon membrane patterned). This deflection increase is believed to be due to a decrease in the residual stress in the actuator.

In order to maximize the deflection, unimorph actuators with different silicon membrane thicknesses were characterized. Actuators with different membrane thicknesses were obtained on the same wafer by selectively etching the silicon membrane to different final thicknesses using the Kapton tape-masked backside etching process [18, 19]. Figure 8 compares the measured actuator strokes with the modeled values. The actuation results from using

Figure 7: Dependence of deflection on silicon membrane thickness for both continuous and patterned PZT films. There is a significant increase in the deflection for the patterned PZT actuator. The data points represent an average of 10 separate measurements on two different pixels within an array.

Figure 8: Actuator stroke as a function of voltage for three different types of actuators. Significant improvement in stroke is achieved using unimorphs with patterned PZT with optimized geometry.
2.5-mm-diameter membrane actuators with (1) continuous PZT film (i.e., Case A) and (2) patterned PZT film (i.e., Case B) are shown as a function of membrane thickness. The experimental results are superimposed over their respective predicted deflection curves from the simulation model. As predicted by our model, the maximum deflections were obtained at intermediate silicon-membrane thicknesses of approximately (1) 15 µm with the continuous PZT film and (2) 10 µm with the patterned PZT film.

PATHFINDER MIRROR MODELING

A general "bulk element" model for an actuated lattice structure was created in order to simulate a pathfinder structure of the active mirror concept. The model envisions two types of elements, nodes and connectors (Figure 9). Nodes are conceptual points in space and/or infinitely stiff junction elements attached with connectors. Connectors are rod-like elements that span two nodes. Connectors have an arbitrary stiffness (a 6 DOF spring constant) and an actuation capability which can either be force-driven (such as a PZT actuator) or displacement driven (such as an linear actuator). The response of the structure to applied stimulus was calculated by fixing the "driven" parameters to their prescribed values and minimizing the total structure energy with respect to the rest of the parameters. In the case of calculating the structure response to linear displacements, the "driven" (fixed) parameters are the linear displacements and the free variables are the coordinates of the free nodes (at least three nodes need to be fixed to stabilize the structure in 3 dimensions). For the purpose of the following study, a simple elastic tensile stiffness was assumed for each connector. The bending and torsional stiffnesses were set to 0 (corresponding to a frictionless hinged attachment at each end). The three rotation angles for each node were therefore not included into the calculation.

Two methods were used to calculate the structure actuation and response. The first method involved numerically minimizing the total structure energy with respect to the sought parameters. The second was a linearized "perturbation" model where a response matrix was calculated once and subsequent Singular Value Decomposition (SVD) was used. Here only the energy minimization method is discussed. A model was developed structure, a stiff lattice supported at three symmetric points, as shown in Figure 10. Larger icosaedra are the three fixed nodes. The dimensions (in centimeters) were chosen to roughly correspond to a structure for a segmented mirror with 1 foot segments. The stiffness of the effective connector spring constant was chosen to mimic a realistic light rod-like element made of a typical metal-like material (Elastic modulus in the 100 GPa range; For reference, 7075 Aluminum has an elastic modulus of 72 GPa, 6Al-4V Titanium - 115 GP, 304 Stainless - 200 GPa), roughly 20 cm long and roughly 10 mm² in cross-section. The resulting stiffness was calculated to be $10^7$ N/m or $10^{10}$ dyne/cm. Since the exemplary structure is over-constrained, a prescribed structure shape can be achieved with various combinations of actuator displacements. However these combinations will have a different amount of stored elastic energy and a different force on each actuator. The method we chose minimizes the total energy of the structure, and thus the forces on the actuators in the commanded state will be minimal. It is advantageous to do so since the linear actuator has a fairly low maximum force limit (e.g. in a 10 mN range). Therefore, to change from one low-energy...
state to another, the structure must follow a path in state space along which the actuator force limits are never exceeded. For a nanometer step, the maximum force on all actuators is around 1 mN. However, if larger step sizes are desired, the stiffness of the connector must be reduced proportionally, i.e., for a 1 µm maximum step size, the stiffness must be reduced by a factor of a thousand. This can be done by designing the connector shape to have reduced stiffness such as by machining flexures into a portion of it. For instance, with the stiffness of $10^5$ N/m, the actuator with 10 mN force can have a 100 nm maximum step size.

Figure 11 shows structure control of the top layer of the structure to the Zernike modes 4 and 7 as examples. A Zernike mode was constructed on a lattice of top layer structure nodes. The other nodes were required to remain in place. Actuator displacement commands were calculated and were subsequently applied, and the structure response to the commands was computed. The difference between the target and the achieved control result is dominated by the round-off error (numerical precision for the calculation shown was set to 14 significant figures).

Figure 10. A model structure. Larger purple icosahedra are the three fixed nodes.

Figure 11. Example of structure control: the top layer nodes required to move in the vertical direction to match Zernike modes composed over the appropriate grid.
CONCLUSIONS

The actuation of a normally-latched, linear microactuator has been demonstrated. Using a pre-stressed tether scheme, the microactuator is capable of maintaining its position when the power is cut off. Observed cumulative stroke exceeded 600 µm. A larger cumulative stroke can be easily achieved because, except for the length of the slider and applied load, there is no conceivable limit of the maximum stroke. Adjustment of incremental step size was demonstrated by varying PZT-stack actuator voltage. Further development is expected to analyze actuator push force, to increase operation speed, to improve linearity, and to improve packaging technique. Using this actuator, a large aperture DM has been developed. DMs consisting of 20-µm thick single-crystal silicon membranes supported by 20 × 20 actuator arrays were fabricated and optically characterized. In all the key parameters, the unimorph MEMS DMs described here can be optimized for delivery of high-quality image correction. Optimized devices should be well suited to the adaptive nulling task, particularly in their low influence function, which allows clean independent correction of nearby spectral channels. Lastly, a pathfinder mirror model has been discussed. This model simulates an ultra-lightweight space telescope mirror with embedded microactuators for active shape correction. The mirror surface figure can be actively corrected by the underlying actuators mechanically coupled via the flexure hinges. The mass density of the mirror including backing structure and actuators will be far less than 1 kg/m².

REFERENCES

