Lightweight, active optics for space and near space

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ABSTRACT

Size, weight, and a lack of adaptability currently hinder the effectiveness of conventional imaging sensors in a number of military applications, including space-based space situational awareness (SSA), intelligence, surveillance, and reconnaissance (ISR), and missile tracking. The development of sensors that are smaller, lighter weight, adaptive, and use less power is critical for the success of future military initiatives. Threat detection systems need the flexibility of a wide FOV for surveillance and situational awareness while simultaneously maintaining high-resolution for target identification and precision tracking from a single, nonmechanical imaging system.

Sandia National Laboratories, the Naval Research Laboratory, Narrascape, Inc., and Composite Mirror Applications, Inc. are at the forefront of active optics research, leading the development of active systems for foveated imaging, nonmechanical zoom, phase diversity, and actively enhanced multi-spectral imaging. Increasing the field-of-view, spatial resolution, spectral capability and system magnification have all been demonstrated with active optics. Adding active components to existing systems can significantly enhance capability in a number of military applications, including night vision, remote sensing and surveillance, chemical/biological detection, and large aperture, space-based systems.

Deployment costs of large aperture systems in space or near-space are directly related to the weight of the system. In order to minimize the weight of conventional primary mirrors and simultaneously achieve an agile system that is capable of true optical zoom without macroscopic moving parts, we are proposing a revolutionary alternative to conventional telescopes where moving lenses/mirrors and gimbals are replaced with lightweight carbon fiber reinforced polymer (CFRP) variable radius-of-curvature mirrors (VRMs) and MEMS deformable mirrors (DMs). CFRP and MEMS DMs can provide a variable effective focal length, generating the flexibility in system magnification that is normally accomplished with mechanical motion. By simply adjusting the actuation of the CFRP VRM and MEMS DM in concert, the focal lengths of these adjustable elements, and thus the magnification of the whole system, can be changed without macroscopic moving parts on a millisecond time scale.

1. INTRODUCTION

To achieve true optical magnification and overcome deficiencies in size, weight, and power requirements, we have previously proposed a revolutionary alternative to conventional mechanical zoom systems where moving lenses/mirrors and gimbals are replaced with active optics [1-2]. Active or adaptive optics [3], such as liquid crystal (LC) spatial light modulators (SLMs) and deformable mirrors (DMs), have previously been proposed and demonstrated as variable focal-length elements [4-6]. Focus control is accomplished by systematically adjusting the optical path across the element to add/subtract quadratic phase variation. In fact, any aberration can be added or subtracted (focus is simply a low order aberration), providing a tremendous amount of flexibility [7-9]. By applying the appropriate voltage to each pixel or actuator, the optical path can be adjusted to create an optical wavefront that approximates the wavefront produced by a conventional lens or mirror. By changing those voltages the focal length of the active element can be varied within the limits set by the dynamic range and the number of pixels or actuators.

Variable focal-length elements can provide the flexibility necessary to change the overall system focal length while maintaining a constant image plane, and therefore vary transverse magnification. Normally, optical zoom is accomplished with mechanical motion. The key to this concept is to create relatively large changes in system magnification with very small changes in the focal lengths of individual elements by leveraging the optical power of conventional optical elements surrounding the active optics. In addition to changing the focal length with a DM or SLM, optical tilt may also be added to the wavefront by appropriately adjusting the voltages. This allows magnification of ***any*** point within the FOV without physically moving some portion of the optical system. Thus, the object to be magnified does not have to lie on the optical axis as in a conventional system.

As the optical tilt can be varied in real time, tracking can be performed without slewing the optical system. Gimbals, which are used to redirect the instantaneous FOV of an imaging system, often weigh as much as the entire optical system. Depending on the size of the optics and the speed of the gimbal, they can draw hundreds or even thousands of Watts to slew large-aperture systems. Even with state-of-the-art gimbals, they take hundreds of milliseconds to slew large angles and may induce unwanted jitter or require momentum compensation. Eliminating gimbals, or at least reducing their requirements, is a major thrust of this research.

While our previous demonstrations have focused on small aperture systems, we are now looking at large aperture systems for telescopes. Utilizing this technique on meter class systems has the potential to improve capability without significantly increasing size, weight, or power requirements. One approach is to utilize a deformable primary, coupled with an active tertiary mirror, to achieve active optical zoom from a large aperture telescope. The requirements on both the primary and secondary mirrors far exceed anything that is currently available. Thus, much of our efforts are focused on the development of composite and MEMS mirrors for this application.

2. MEMS MIRRORS

Recent development of optical MEMS mirrors at Sandia National Laboratories includes an array of 91 piston-tip-tilt micromirrors [10], along with the electronics control board, shown in Fig. 1. The chip was packaged in a 256 pin PGA using automated die attach and wire bonding equipment. The array of 0.5-mm micromirrors has a clear aperture of 3.9-mm and was fabricated at Sandia using the SUMMiT™ V process. The micromirrors are driven by three linear actuators, each with a stroke of ~8-µm, which allow each micromirror to move axially and to be tipped and tilted.

Sandia has several research efforts that are under way: 1) the mirror curvature introduced when the metal reflective coating is applied is being compensated by pre-bending the mirrors before coating, 2) advanced micromirrors with 27-µm stroke are being developed and have been demonstrated, and 3) on-chip, under-micromirror electronics are being prototyped.

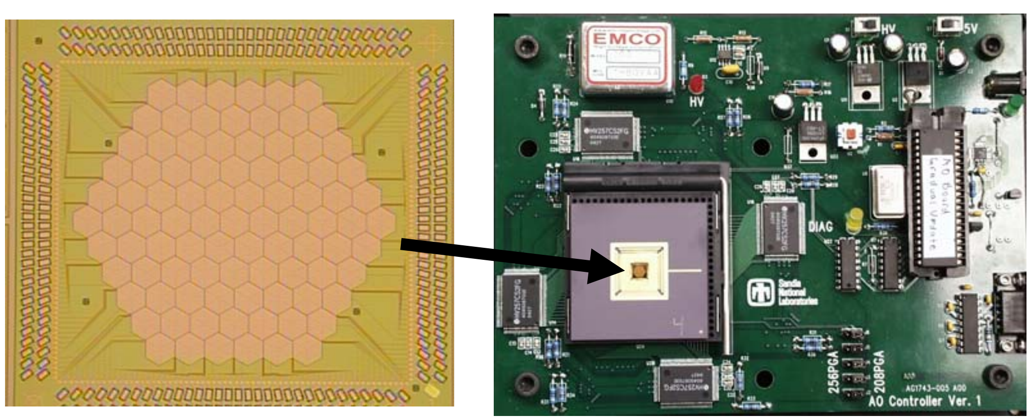


Fig. 1. 91 element hexagonal piston-tip-tilt mirror array with a ~4 mm active aperture packaged on controller board.

Fig. 2 shows 3D images of 1st and 3rd order aberrations created with a 61-micromirror array (note this is a different mirror than the one shown in Fig. 1). The actuators under these micromirrors each have a 27-µm stroke, which is the largest stroke MEMS mirror available, to the best of our knowledge. The images presented in Fig. 2 show wavefront data taken from each mirror segment and subsequently stitched together. This data was taken with a WYKO white-light interferometer.

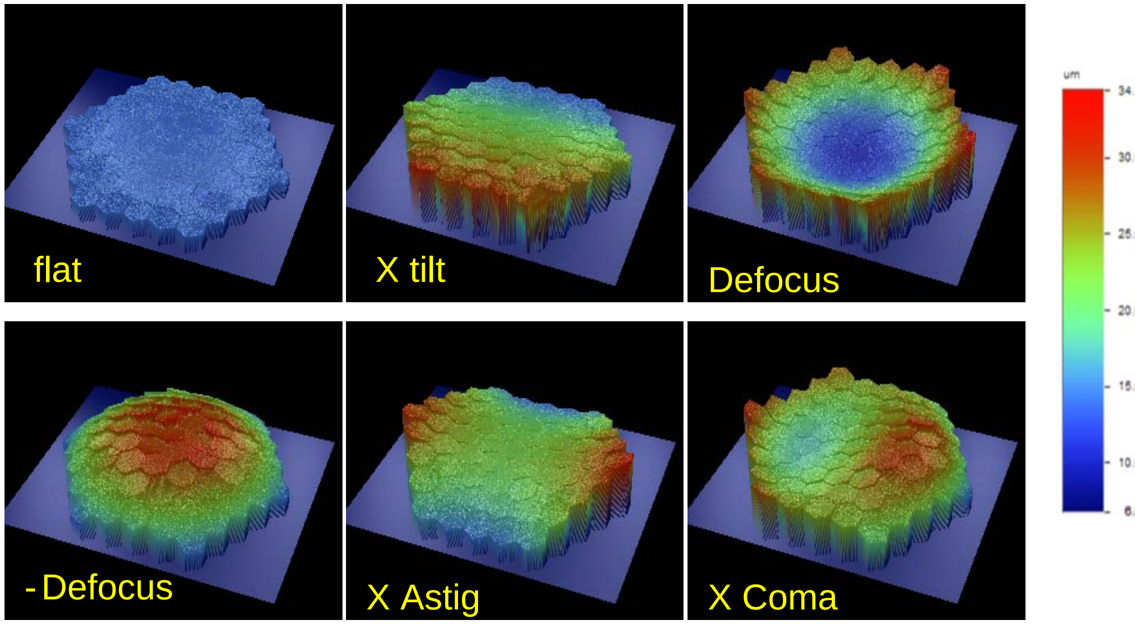


Fig. 2: Zernike aberrations created with an array of 61 piston-tip-tilt micromirrors with 27-µm stroke

3. COMPOSITE MIRRORS

As size and weight are a premium for space-based applications, the development of light-weight, variable radius of curvature mirrors is an important component in a space-based active optical system. Composite Mirror Applications (CMA), working with the Naval Research Laboratory (NRL), is currently developing carbon fiber reinforced polymer (CFRP) mirrors for the Naval Prototype Optical Interferometer (NPOI). NPOI is the world's only long baseline optical interferometer operating in the visible region, i.e. wavelengths below 0.8 µm. It is also the only optical interferometer able to recombine up to six beams, from different apertures, simultaneously.

Using carbon fiber construction for all components, including optics, CMA has delivered a 0.4 meter prototype telescope for testing, shown in Fig. 3. CMA is currently fabricating a 1.4 meter telescope that will be less than 300 pounds. As all components of the telescope, including optics, are constructed from composite materials having a low coefficient of thermal expansion, dimensional changes due to temperature variations can be minimized. Also, since all optics are made from a single high precision tool, duplicate components can be manufactured for much less than traditional steel and glass telescopes [11].

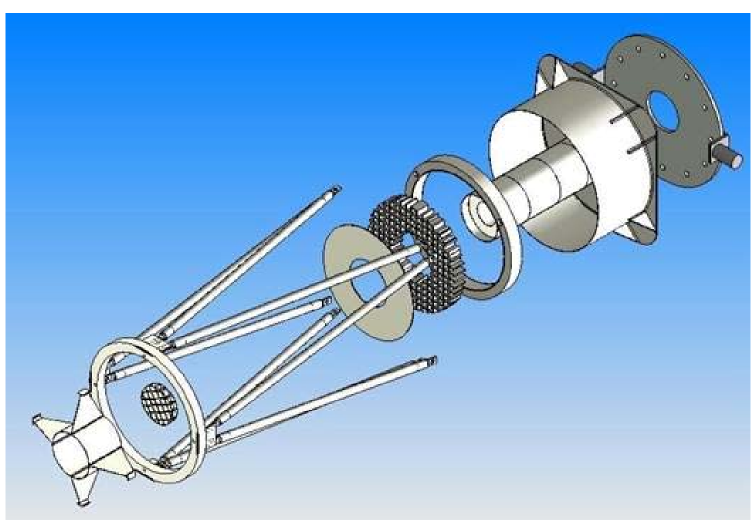


Fig. 3. Exploded view of 0.4m CFRP telescope prototype

The optical telescope assembly (OTA), including all structural supports and optics, weighs roughly 10 Kg. As a comparison, a commercially available 0.4m Meade telescope weighs roughly 57 Kg. This lower mass and lower rotational inertia helps reduce the mount mass, and in turn, reduces the drive power requirements for tracking. The 0.4m system shown in Fig. 4 includes the drive motors, an electronics rack constructed from CFRP and aluminum, and a CFRP AO box and breadboard.

The performance of the drive system is dependent on three critical components: the drive motors and geometry, the encoders, and the servo electronics. A direct drive system was chosen for maximum stiffness and pointing precision. This drive system is realized with ultrasonic piezoelectric motors manufactured by Nanomotion, Ltd. driving a static ceramic ring. This unique drive configuration is possible because of the low mass (and low rotational inertia) of the system. Using the specifications provided by Nanomotion, the maximum slew speed is expected to exceed 20 deg/s with tracking speed exceeding 1 deg/sec.

The encoders are Renishaw optical encoders with a readout resolution of 0.04 arcseconds. The system accuracy is quoted as about 1 arcsecond which are largely systematic errors which can be compensated for in the mount drive model. The servo is controlled by a commercial control card designed for high accuracy and ease of implementation.

Fig. 4. Lightweight telescope (in black) mounted on portable AO system (white) and lightweight mount (blue fork).

4. ACTIVE OPTICAL ZOOM

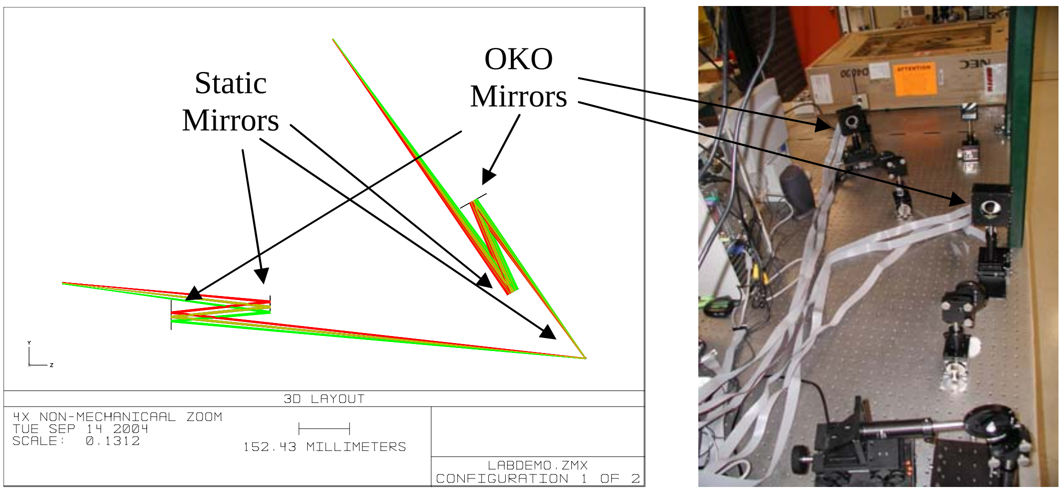
To show how a CFRP telescope could be used to achieve active optical zoom, we have investigated the first order design tradespace. The conclusions were:

1. To preserve the system numerical aperture (f-number), the entrance pupil of the system must grow in proportion to the zoom ratio. The primary mirror must be oversized substantially (relative to the unzoomed state), at least in proportion to the zoom ratio, to accommodate the larger entrance pupil.

2. The second active mirror (the one closest to the detector) must be at the aperture stop, or located an image of the aperture stop.

3. For a given field-of-view, unzoomed entrance pupil diameter, and zoom ratio, there is a fixed relationship between the magnitude of the mirror deformations on the first and second active mirrors. Furthermore, there is a minimum deformation on the first active mirror. The magnitude of the deformations cannot be changed by using telescopes or reimaging optics, or by moving the active mirrors deeper into the system.

In order to demonstrate the concept with an all-reflective system, we utilized small, electrostatically-driven micromachined deformable membrane mirrors (MDMMs) from OKO Technologies along with conventional spherical mirrors in our optical design. Custom software was developed by Narrascape to simultaneously control both MDMMs in the optical setup. Designing an optical system with significant magnification around the limited capabilities of these mirrors was our next technical hurdle. As with the LC SLMs, deformable mirrors, both MDMMs and conventional, can operate over very limited focal-length ranges, and creating large changes in system magnification with small changes in the focal lengths of individual components proved to be a difficult task. However, by leveraging those small changes in focal length with high optical-power static elements, we were able to successfully design an all-reflective, active optical zoom sensor with 4X magnification and 2X increase in resolution, shown in Fig. 5(a).



(a) (b)

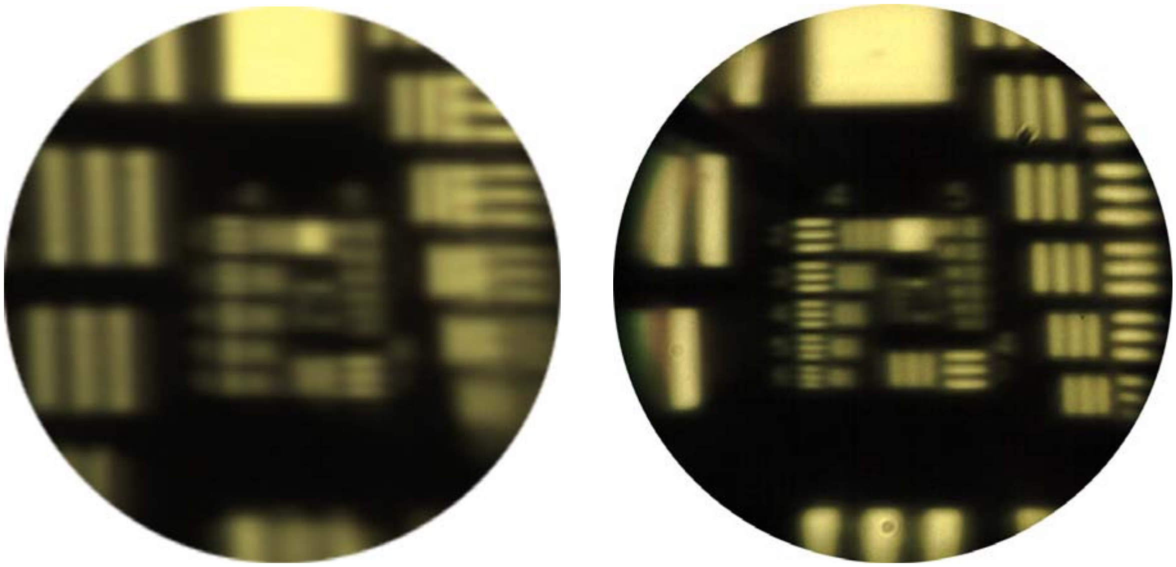
Fig. 5. (a) ZEMAX® and (b) experimental layouts of the 4X active optical zoom.

Fig. 5 shows the ZEMAX® and experimental layout of the active optical zoom demonstration. This system consists of two 59-channel OKO MDMMs and 3 static spherical mirrors with focal lengths of 1.0m, -0.2m, and 1.0 m. The calculated magnification for this system is 4X with a corresponding increase in resolution of approximately 2X. The resulting images, shown in Fig. 6, show an increase in magnification of about 3.8X. Here Groups 2-5 of an AF bar chart are imaged on the camera. The difference in resolution between the horizontal bars and vertical bars is due to the off-axis design, and likely some slight misalignment; because of the off-axis design, the tolerances are extremely tight in the x-z plane (i.e. the plane of the optical bench). Note that the camera gain is manually adjusted between (a) and (b) for each of the figures.

(a) (b)

Fig. 6. (a) Unzoomed and (b) zoomed images taken with active optical zoom system. Nothing was changed between (a) and (b) except the voltages that were applied to the actuators and the gain on the camera.

Note that the poor quality at the edges of the images, particularly noticeable in corners of Fig. 4(a), is due to the residual errors at the edge of the MDMMs. Because these mirrors are attached at this boundary, it is very difficult to remove all of the aberrations at the edges. Ideally, we would aperture the mirror down and only use the central ~80% of the mirrored surface. If we restrict the FOV of our system, we can eliminate some of the edge effects. Fig. 7 shows the central area of the bar chart with and without active zoom. Here the unzoomed image, Fig. 7(a), is digitally expanded 4X in order to compare resolution with the zoomed images. In this case, the changes in image brightness/color are simply due to manual adjustments of the camera gain.



(a) (b)

Fig. 7. Restricted FOV images taken with active optical zoom system in (a) unzoomed (electronically expanded by 4X) and (b) zoomed configurations. Note the increase in resolution capability.

There is nearly two times the resolution capability in the zoomed case, consistent with MTF calculations. The highest resolvable set of horizontal bars in the unzoomed image from the active optical zoom system, 7(a), is Group 4-2 at 17.95 lp/mm (as measured in the object plane). This is consistent with the calculated cut-off frequency of 23 lp/mm and an MTF that falls below 10% at 20 lp/mm. In the zoomed case, 7(b), we can resolve Group 5-1 at 32 lp/mm. This is again consistent with a calculated cut-off frequency of 43 lp/mm and an MTF that falls below 10% at 36 lp/mm.

5. CONCLUSIONS

Light weight, CFRP mirrors may be useful as large aperture, variable radius of curvature mirrors in an active optical system. A first order analysis of two-mirror active zoom systems shows that there is a fixed relation between the deformations of the two active mirrors. This relation is independent of system design details and depends only on the system Lagrange invariant and the zoom ratio. Auxiliary optics can reduce the overall length of a system, but cannot reduce the required deformation of the two mirrors. The second active mirror must be located at the aperture stop, or at an image of the aperture stop, to preserve the numerical aperture of the system. Under this condition, there is a minimum deformation on the first active mirror which cannot be altered by auxiliary optics. A fixed detector size and system numerical aperture (f-number) require that the entrance pupil increase in proportion to the zoom ratio. Closed form expressions for the focal length, location, and mirror deformation have been given for a two-mirror system. Preliminary demonstrations using small aperture, micromachined deformable membrane mirrors have shown 4X magnification with 2X increase in resolution, consistent with modeling.

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REFERENCES

1. Wick, D.V. and Martinez, T., "Adaptive Optical Zoom," *Optical Engineering*, **43**(1), 8-9 (2004).
2. Wick, D.V., Martinez, T., Payne, D.M., Sweatt, W.C., and Restaino, S.R., "Active optical zoom system," *Proc. of SPIE*, **5798,** 151-157(2005).
3. Tyson, R.K., *Principles of Adaptive Optics, Second Edition*, Academic Press, San Diego (1998).
4. Naumov, A.F., Love, G.D., Loktev, M.Y., and Vladimirov, F.L., "Control optimization of spherical modal liquid crystal lenses ," *Opt. Express* **4**(9)**,** 344-352 (1999).
5. Laude, V., "Twisted-nematic liquid-crystal pixilated lens," *Opt. Comm*. **153**, 134-152 (1998).
6. Takaki, Y. and Ohzu, H., "Liquid-crystal active lens: a reconfigurable lens employing a phase modulator," *Opt. Comm*. **126**, 123-134 (1996).
7. Wick, D.V., Martinez, T., Restaino, S.R., and Stone, B.R., "Foveated imaging demonstration," *Opt. Express*, **10**, 60-65 (2002).
8. Love, G.D. "Wave-front correction and production of Zernike modes with a liquid-crystal spatial light modulator," *Appl. Opt*. **36**, 1517-1524 (1997).
9. Pepper, D.M., Gaeta, C.J., and Mitchell, P.V., "Real-Time Holography, Innovative Adaptive Optics, and Compensated Optical Processors Using Spatial Light Modulators," Chap. 14 in *Spatial Light Modulator Technology - Materials, Devices, and Applications*, U. Efron, ed., Marcel Dekker, Inc., New York (1995).
10. Sweatt, W.C., *Reduction of Zernike Wavefront Errors Using a Micromirror Array*, Optical Engineering vol.44, no.9 98001-1-6 (2005.).
11. Andrews J.R., Penado F.E., Broome S.T., Wilcox C.C., Restaino S.R., Martinez T., Teare S.W., Santiago F. "Characterization of the lightweight telescope developed for the NPOI", *Proc. SPIE Vol.* **6267,** (2006).