ACTUATED HYBRID MIRROR TECHNOLOGY

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I INTRODUCTION

Developments over the past five to ten years have led to the successful demonstration of the technologies needed for Actuated Hybrid Mirrors (AHMs), providing a new option to conventional glass primary mirror assemblies (PMAs) for space telescopes[1]. In its current form, as illustrated in Figure 1, the AHM consists of the following elements:

- A rib-stiffened silicon carbide (SiC) substrate, cast to near net shape and generated to the required optical figure.
- A metallic nanolaminate facesheet deposited on a precision mandrel and adhesively bonded to the surface of the substrate to provide the optical finish of the mirror.
- Surface parallel actuators (SPAs) embedded in the substrate ribs and used to actively control the final figure of the mirror.
- A sensing system (typically, but not necessarily, a wavefront sensor) to determine the real time figure of the mirror and provide the control inputs needed by the actuation system.

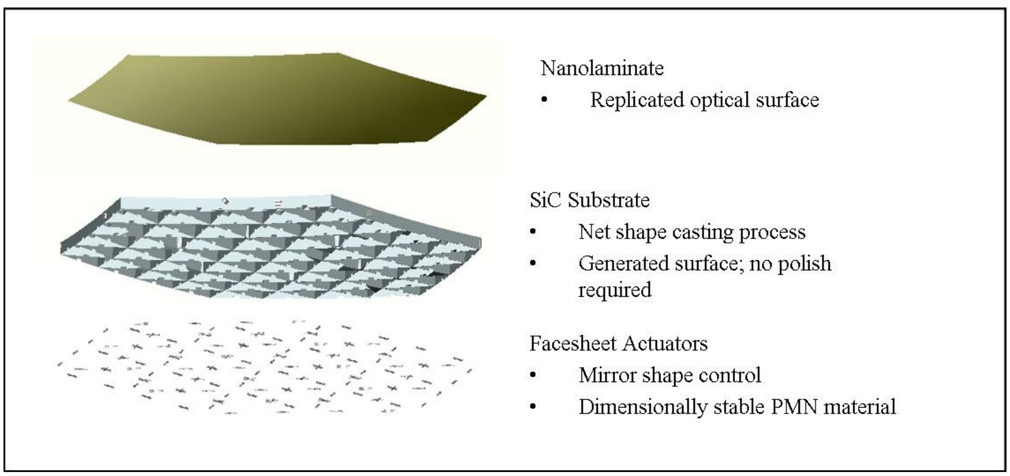

Figure 1: Actuated Hybrid Mirror Concept

[1] Although AHMs have been developed for space applications purposes, they should also be considered for ground telescopes.

Because of the need for a precision deposition mandrel[2] for production of the nanolaminate facesheet, this technology is generally most suited to two classes of applications, both of which require the fabrication of multiple mirrors or mirror segments that have identical (or nearly identical) prescriptions:

- Very large space telescope PMAs that must be formed through the deployment of multiple segments due to launch vehicle size limitations. Examples of telescope concepts that could benefit from this capability include the Single Aperture Far Infrared (SAFIR) telescope and the Advanced Technology Large-Aperture Space Telescope (ATLAST)
- Architectures that consist of a number of smaller telescopes (i.e., within the volumetric capability of an existing launch vehicle) that can employ nearly identical monolithic PMAs for multiple different science applications or that are proliferated for survey or time sensitive applications. For example, AHM technology could enable fabrication of multiple telescopes for an external occulter exoplanet detection system, increasing the efficiency of both exoplanet detection and general astronomical observations, as well as serving as the basis for a Joint Dark Energy Mission (JDEM).

These two cases do not exhaust the utility range of the AHM, however. Because it enables both rapid mirror replication once program tooling is in place as well as real time control of mirror figures in operating systems, AHM technology can also provide economic benefits, including:

- An ability to relax manufacturing constraints on space telescope primary mirrors since they can be controlled to the higher precision required for a mission once placed into operation.
- A manufacturing capability to rapidly produce duplicate PMAs to rapidly respond to changing circumstances, such as:
  - Replacement for a lost or failed vehicle.
  - Supplement an initially small architecture with additional vehicles, either in accordance with a planned strategy or to realize unexpected opportunities.
  - Enable flight demonstrations that can, upon success, be expanded into a more extensive operational architecture

Of course, as with any technology, the AHM has its own set of limitations. These include:

- Although the initial impetus for the development of the AHM was to produce lightweight mirrors, the technology of conventional passive mirrors (particularly in glass) has also advanced, and the two technologies are currently quite competitive, both being able to achieve areal densities in the same approximate range (10 – 15 kg/m^2).

[2] Necessarily convex for a primary mirror, and therefore generally more difficult and costly to fabricate (and measure) than a single conventional passive primary mirror.

- The AHM requires the added complexity of a sensing and control system.[3]
- Space qualification of the technology and mirror system.
- AHM technology will require significant development before it can be considered for cryogenic applications, specifically due to the critical role played by the adhesive bond between the nanolaminate facesheet and the SiC substrate.

II CURRENT STATE OF THE ART

The AHM was first developed early in the current century by a merger of two technologies: the actuated Integrated Meniscus Mirror (1) and magnetron sputtering of thick, metallic nanolaminate optical facesheets (2). This development occurred through collaboration between Lawrence Livermore National Laboratories (the nanolaminates), and Xinetics, Inc., a private corporation (the meniscus mirrors), and is graphically illustrated in Figure 2.

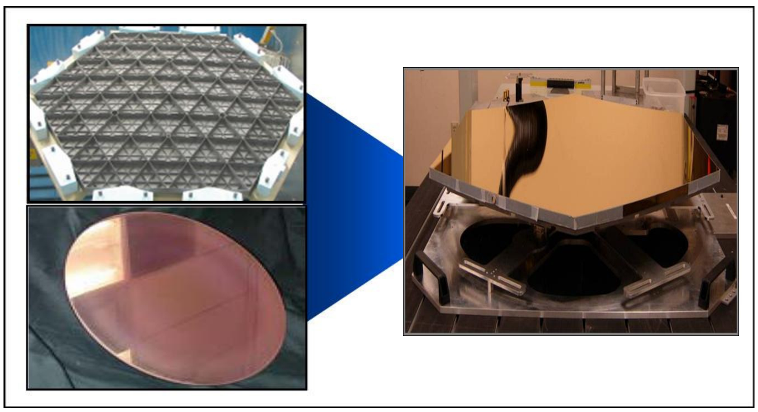

Figure 2. Demonstration of the AHM Concept

Over the past several years, these Actuated Hybrid Mirrors have evolved through a range of sizes, establishing the ability to scale their manufacture up to the 1.5 meter diameter class. In addition, the infrastructure that has been assembled will enable further scale-up to mirrors with dimensions greater than 2 meters as the need arises. AHMs have been fabricated as flat, spherical, and aspherical (both on- and off-axis) mirrors and mirror segments. The substrate employed has been reaction bonded silicon carbide fabricated by what is now Northrop Grumman Xinetics (NGX) in Devens, Massachusetts, although other substrate materials have been considered (see below). The nanolaminate facesheets have been deposited with alternating layers of zirconium and zirconium-copper (Zr/ZrCu) by Lawrence Livermore National Laboratory (LLNL), Livermore, California[4]. Actuation is accomplished using standard NGX lead magnesium niobate (PMN) electrostrictive actuators, and adhesion is provided by an NGX proprietary epoxy.

[3] Note that these sensing and control systems are included in the areal density claimed for the AHM in the preceding sub-paragraph.
[4] For production purposes, the capability to deposit these nanolaminates has recently been installed at NGX as well.

Next Steps. The Naval Postgraduate School (NPS) will soon install a large AHM for further experimentation (e.g., for wavefront sensing and control systems). In addition to this technology testbed, the most important next step to enabling future applications of AHM technology is to demonstrate fabrication at carefully judged larger scales up to the full capacity of the existing infrastructure. Following the conservative methodology of earlier AHM programs, this should include mirrors fabricated in on-axis and off-axis, spherical and aspherical configurations. To this end, designs have been already been developed for mirrors at apertures up to 1.5 meters, and some tooling has been acquired to enable near term fabrication. In addition, the materials and processes required for manufacture of AHMs are currently passing through a rigorous space qualification process to ensure that their survival and operational capabilities in all phases of spaceflight have been demonstrated to the level required.

III AHM TECHNOLOGY PROJECTIONS

Finally, several technology development programs are being conducted to refine and enhance the foundational AHM technologies, extending and simplifying their applications to future operational programs. These include the development of different materials for AHM components, enhanced actuation, better sensing and control technologies, and more flexible manufacturing techniques. The following paragraphs provide examples of each of these development areas.

1. New Materials. With few exceptions, AHMs fabricated to date have all been based upon substrates cast from silicon carbide, a material with a low but non-zero coefficient of thermal expansion (CTE) that complicates mirror design and thermal control. For this reason (and potentially to expedite low-cost fabrication of AHMs while further reducing their areal densities), development of AHMs utilizing Carbon Fiber Reinforced Polymers (CFRP)[5] substrates is now underway (and accounts for the "few exceptions" noted in the preceding sentence). Pathfinder mirrors with 45 cm diameters have been fabricated, and the future direction of this program will depend upon the success in fabricating an optical quality CFRP AHM with an aperture of 75 cm. This part of the program is scheduled to be completed in the late summer to early autumn of 2009.

2. Enhanced Actuation. In the simplest version of an AHM, the only actuators are those embedded in the vertical ribs on the back of the substrate. These actuators impart a moment to the ribs, thus altering the curvature of the mirror at relatively low spatial frequencies. This low frequency correction induces surface errors at higher spatial frequencies that (depending upon their magnitudes) limit the ability to control the low frequency surface figure. To counter this effect, smaller actuators are being developed to be embedded in intimate contact with the back side of the substrate facesheet (i.e., in the triangular spaces between the ribs, visible in Figure 2 above). These actuators (currently designated as Compound Actuators), which can be either Surface Parallel Actuators (SPAs) or Surface Normal Actuators (SNAs), being smaller than the SPAs in the ribs proper, can be used to control higher frequency surface errors. The effectiveness and

[5] More specifically, Graphite Epoxy (GrEp) composites.

range of applicability of Compound Actuators is currently the subject of simulation and experimental development programs scheduled to extend at least into the winter of 2009.

3. Flexible Manufacturing. Experience with AHMs has established quite firmly that one of the most difficult elements (perhaps the most challenging element) of an AHM program is fabrication of the mandrel to be used for nanolaminate deposition. The mandrel must be convex, larger than the mirror (or segment) to be fabricated, precisely characterized, and must possess a surface finish of higher quality than that required of the final mirror itself. These facts imply that fabrication of the mandrel (including metrology) is the basic long lead item of an AHM program, and will generally be more costly and demanding than conventional fabrication of a single glass mirror to the same specifications as required of the AHM. From this results the statement in the Introduction to the effect that AHM technology is generally applicable only to programs that require multiple mirrors or segments built to nearly identical prescriptions.

It has been noted that this issue could be alleviated to some degree by at least two technical advances currently under development:

- An inexpensive, flexible metrology system for the accurate and repeatable characterization of convex optical surfaces. A four point stitching profilometry[6] technology has been developed by Bauer Associates of Natick, Massachusetts, and a program is currently underway to validate this technology and determine its limits of applicability (e.g., precision, maximum radius of curvature and size of the test item, etc.).
- Direct application of the foundational actuated mirror[7] technology to fabrication of the mandrel itself. That is, using the same technology as employed to fabricate and actuate the SiC substrates for AHMs, it may be possible to fabricate a convex mandrel to a "general" prescription, polish it to the required optical quality, and then actuate it to any of a number of prescriptions required for deposition of a family of AHM nanolaminate facesheets. While such a mandrel would face more serious difficulties than those faced by a mirror substrate (the mandrel must rotate at high speed, endure high and variable temperatures in a deposition chamber, etc.), the potential payoff is sufficient to support a current investigation expected to yield a general indication of the concept's basic feasibility by the autumn of 2009.

IV CONCLUSION

The Actuated Hybrid Mirror architecture offers a potential for a new approach to the design, development, and manufacture of space telescopes, both large and small. Combined with imaginative deployment technologies, it may enable the construction and launch of very large space telescopes with multiple segment primary mirrors. In addition, it can also enable space telescope architectures that consist of a series of smaller, single monolithic segment telescopes, none capable of the scientific productivity of

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[6] Which is applicable to concave as well as convex surfaces.
[7] Not the complete AHM technology, since no nanolaminate facesheet would be incorporated.

Observatories such as Hubble, Spitzer, or the James Webb Space Telescope (JWST), but which as a whole could contribute a capability to survey broad regions of space, monitor time dependent phenomena, and react to unexpected events providing vital new insights into astronomy (and, quite possibly, new questions).

REFERENCES

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