NGST Mirror System Demonstrator
from
the University of Arizona

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ABSTRACT

Future space telescopes require primary mirrors that are much lighter than those currently being manufactured. They also must maintain optical tolerances while operating at cryogenic temperatures. We present a Mirror System Demonstrator for the Next Generation Space Telescope (NGST) that uses a thin glass facesheet with active control to achieve low mass and high surface quality. A 2 mm thick glass facesheet is controlled by miniature actuators and held together by a rigid carbon fiber frame. The 2-m diameter mirror system weighs only 13 kg/m^2, including the glass, supports, actuators, support structure, and cabling. We present the status of the development and testing of this revolutionary mirror.

Keywords: space optics, optical fabrication, gossamer optics

1. INTRODUCTION

The University of Arizona is manufacturing a 2-meter mirror as a technology demonstration for the Next Generation Space Telescope NGST. This telescope requires new technology for the optics for several reasons. Conventional mirrors are much too heavy – the 2.4–m primary mirror for Hubble Space Telescope weighs 830 kg, yet the 6-m NGST primary with six times the area, must weigh considerably less than this. The size of the NGST primary mirror is larger than available launch vehicles, so the mirror must be made in segments, then assembled in space. NGST will operate at cryogenic temperatures around 35K. The optics and mounting hardware must be made from materials that perform well at these extreme temperatures, yet it must operate at ambient temperatures for integration and testing. The NGST will operate in solar orbit, where there is no opportunity for repairs.

The NGST Mirror System Demonstrator, fabricated at the University of Arizona, meets these goals using a highly active system that builds on years of experience making optics for ground based telescopes. The Steward Observatory Mirror Lab has manufactured primary mirrors as large as 8.4-m diameter and as fast as *f*/1. Also, the ability to manufacture glass mirrors that only a few millimeters thick has been developed for use as deformable mirrors for adaptive optics. [1,2]

The mirror system concept, shown in Figure 1, uses a curved glass facesheet with a reflective coating as the optical surface.[3] This element is fabricated as a low-stress optic from a thicker glass substrate. The shape of this facesheet is maintained using active control via an array of stiff position actuators. The NMSD uses remotely driven fine pitch screws for the actuators because they make small, reproducible steps; they are stiff and require no power to hold their position; and they work at cryogenic temperatures. The system structural rigidity is maintained

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using a highly optimized composite backing structure. A 50-cm prototype mirror of this type was built using a 2-mm facesheet made of Zerodur glass. This mirror, shown in Fig. 2, was demonstrated to have figure errors of about 50 nm rms, dominated by gravitational effects which are of course released in space.

In operation, the precise shape of the mirror is controlled by the actuators, based on input from a wavefront sensor. The active control, based on star light, compensates for substrate stability, fabrication errors, and deployment errors. Numerous techniques have been demonstrated for making real time wavefront measurements with the fidelity needed for NGST.[4]

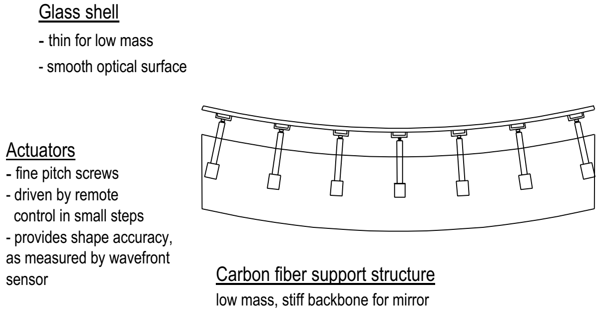

Figure 1. Active mirror concept showing glass facesheet, actuators, and support structure.

Figure 2. A prototype mirror, weighing about 20 kg/m^2. This mirror used a 2-mm Zerodur facesheet on 36 actuators and a composite support structure.

The NMSD takes advantage of active control to make the fabrication easier. The active control eases requirements for thermal stability of the structure, which could see large temperature changes or thermal gradients. It also accommodates changes in shape due to material instability over the life of the mirror. In addition, the facesheet does not have to be initially polished accurately on large scales because it can be deformed into shape. Basically, anything that negatively affects the mirror surface can be corrected.

The use of multiple actuators at first glance appears to introduce significant risk. In fact, more actuators are installed than would be necessary to control the mirror. If an actuator fails, it can be disengaged and retracted from use. The loss of any one actuator, or even pairs of adjacent actuators, does not significantly affect the mirror shape. Also, the actuators require no voltage or command to hold their positions; if the carbon fiber structure is stable for weeks, then the surface shape will not adjusted for weeks.

A system drawing of the University of Arizona NMSD is shown in Figure 3. This mirror uses a composite support structure, 166 actuators, and a 2-mm thick glass shell. The entire system weighs only 13 kg/m^2.

2. SYSTEM DESIGN

The design of the NMSD followed a process to optimize performance with a given mass budget. This optimization assumes a fixed mass budget and we design for optimal surface figure, high resonant frequencies, and launch survival by allocating this mass optimally to actuators, support structure, and facesheet thickness.

2.1 ACTUATOR DENSITY

The most important tradeoff in the design involves the number of actuators. Ideally, the facesheet will be perfectly manufactured and will require zero force to maintain its shape in space. In reality, the facesheet will have strain due to the fabrication process and variations of the material properties within the blank. These tend to warp the facesheet and require corrective forces to maintain the correct shape of the facesheet. The actuators apply this force at discrete locations and can cause local bumps in the surface at the period of the actuators. The actuators can correct only errors that occur with scales larger then actuator spacing. We used a statistical model of the fabrication errors in terms of a power spectral density. This is coupled with finite element analysis that simulates the effects of fabrication errors and material property variations as functions of spatial frequency.

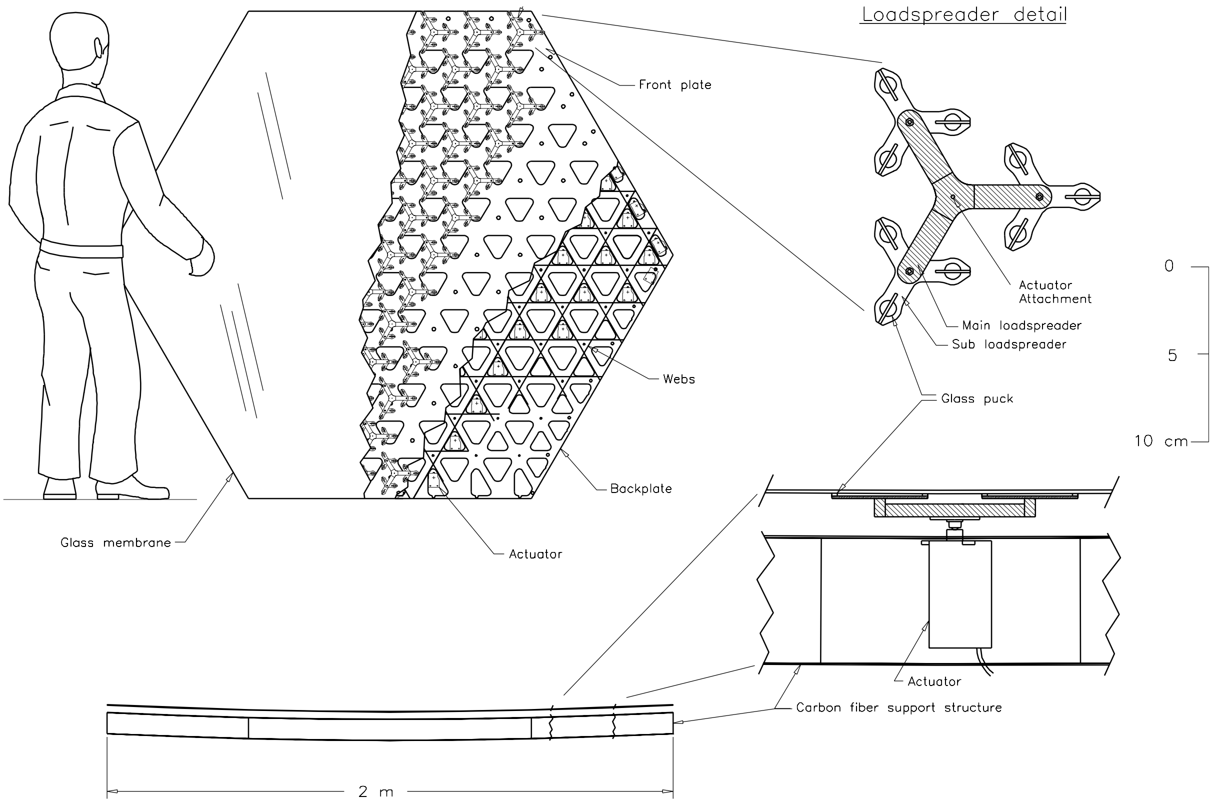

Figure 3. University of Arizona NMSD

2.2 SELECTION OF GLASS

We have chosen borosilicate glass for the cryogenic mirror because it has zero CTE (coefficient of thermal expansion) at the operating temperature of 35 K. Other glasses have better performance over a wider range, but the borosilicate is best in the NGST operating range, it is obtainable at moderate cost, and it is made with excellent CTE homogeneity.

2.3 ATTACHMENT TO GLASS

The engineering of the glass attachment has proven to be quite difficult due to the sensitivity of the thin glass. This hardware must constrain the surface in the normal direction without applying lateral forces or moments of any significance. In addition, the hardware provides the launch support. The NMSD with 2 mm glass facesheet has 450 support points per square meter, each no more than 6 mm in diameter to enable us to withstand 30 g quasi static loads with a factor of safety of 3. The 6 mm diameter limit is based on analysis of the effects of CTE mismatch between the facesheet and the bonded on buttons and the effects of the contraction of an 0.013 mm layer of PR-1564 adhesive. We require far fewer supports to maintain figure during operation, 50 actuators/m^2 coupled to the facesheet through a 3 point loadspreader would be adequate.

The NMSD attachments use lightly loaded joints to provide surface normal restraint at 450 point/m^2 while limiting extraneous loads to acceptable levels. Each loadspreader assembly is coupled to its actuator through a magnetically preloaded ball bearing. This minimizes lateral forces and moments that would be applied to the loadspreader. The loadspreader assembly is attached to the facesheet by being loosely fitted over nine buttons bonded to the back of the facesheet. It is captured in this position by caps bonded onto the buttons. Compliant O-rings between each button and loadspreader transmit lateral launch loads but use sufficient clearance to prevent anything more than incidental lateral contact during operation. Surface normal loads are transmitted by lightly preloading the loadspreader to each of the button caps.

The loadspreader assembly couples nine points on the facesheet to a single actuator. It consists of a main loadspreader that couples the actuator to three sub-loadspreaders. As noted above, the actuator to loadspreader interface uses a magnetically preloaded ball bearing to transmit only surface normal forces. The preload level ensures that adequate tensile forces can be transmitted to the facesheet but prevents the accumulation of tensile forces from becoming dangerous (if all the actuators but one pull back, the facesheet still cannot be damaged). For launch, the loadspreader is further restrained by extending the actuator until three cables (per actuator) are brought to full extension. This disables the tension breakaway and enables the transfer of lateral loads through the cables making the assembly capable of withstanding launch loads.

The connection between the main and sub-loadspreaders is a simple spherical joint. Frictional moments must be low across this joint and surface normal stiffness must be high. These requirements are satisfied by a lightly preloaded, dry lubed joint. The sub-loadspreaders themselves are complicated by the demands for stiffness and the need to avoid applying moments at the button/cap interface to the facesheet. The moment is minimized by using a bridge that goes over the button cap and bears down against the middle of the cap. A spring washer on the underside of the cap pushes the sub-loadspreader toward the facesheet, forcing contact at the bridge. The resolved forces on both sides of the button cap are well centered. The bridge piece always bears against the middle of the cap, and the curved spring washer has a very low moment stiffness that minimizes any applied moment.

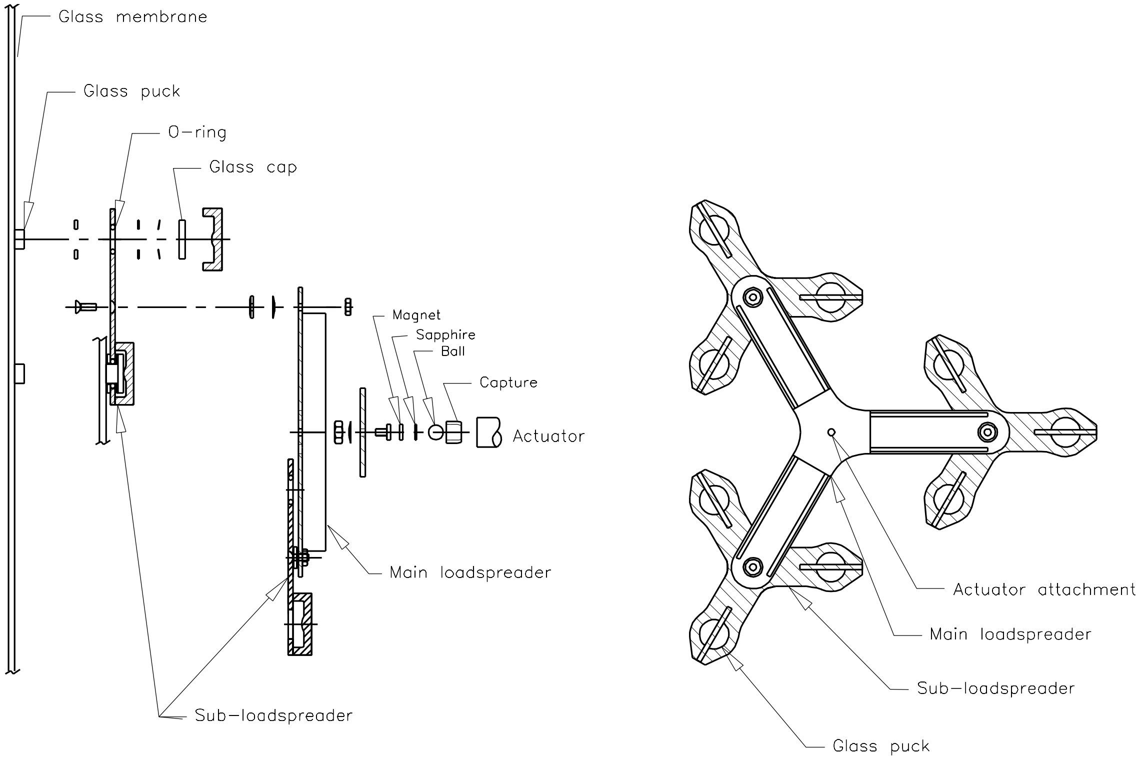

Figure 4. Exploded side view and assembly drawing showing the 9-point load spreaders and their attachment to the glass facesheet.

The launch loads of the glass facesheet are taken through the actuators. This requires an additional set of attachments that keep the magnet-ball in compression and can take lateral loads. We solved this issue using cables that are pre-tensioned before launch to pre-load the actuator. As the actuators retract, the cables will go slack. The facesheet is then supported only by the actuators the constrain motion normal to the surface and three tangent arms that prevent lateral motion and rotation.

This design meets the often conflicting requirements of cryogenic operation with excellent surface figure while providing a stiff constraint to surface normal motion and adequate strength to withstand launch loads. Lateral positioning during operation is provided by a separate system of three tangent rods coupling the facesheet to the cell. This system includes a breakaway mechanism and auxiliary actuators to prevent overstress during launch and handling operations.

3. GLASS FACESHEET

The most challenging aspect of this mirror was the manufacture of the 2-mm thick glass facesheet. The sequence for manufacturing the glass is shown in Fig. 5. The basic concept is to block the glass facesheet down to a rigid blocking body, then to perform all grinding and polishing operations to achieve the correct figure and thickness. The principal difficulties are listed in Table 1 below.

Table 1. Main difficulties for glass fabrication

Operation	Reason for difficulty	Solution
Obtaining low stress blank	Tight requirements on homogeneity	Custom casting from single melt
Blocking	Must be stress free	Use distributed support, block with pitch
Generating	Potential for large forces	Make light cuts
Deblocking	Difficult transition of thin glass – from being rigidly blocked to being held in a different way	Use flotation in hot oil

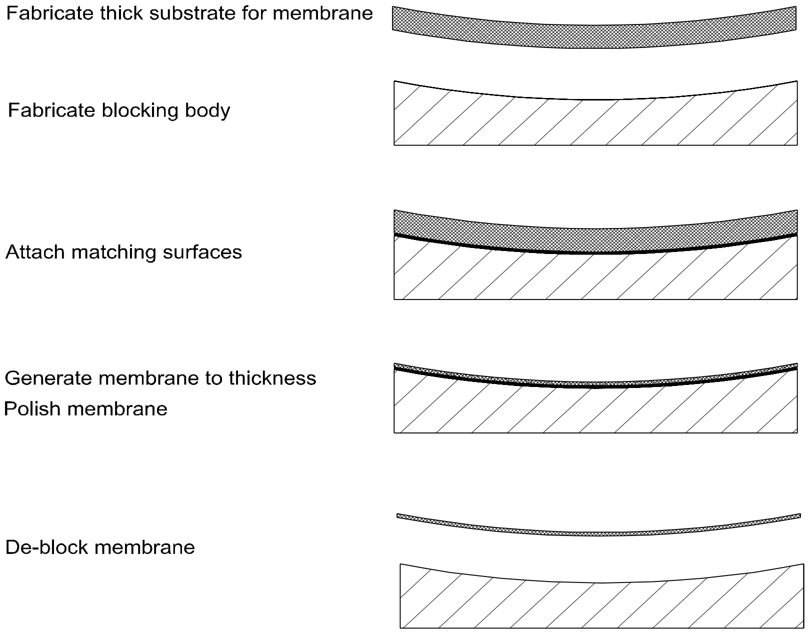

Figure 5. Sequence used to fabricate the 2-mm thick glass facesheet for the NMSD

The 2.2-m diameter, 50 mm thick blank was cast of E6 borosilicate glass from Ohara in the spinning oven at the University of Arizona. The casting was made from a single melt of glass to insure the highest possible homogeneity. These operations are shown in Fig. 6.

Figure 6. Manufacture of the E6 blank for the NMSD shell, including mold construction, preparation to flow out glass, and final substrate.

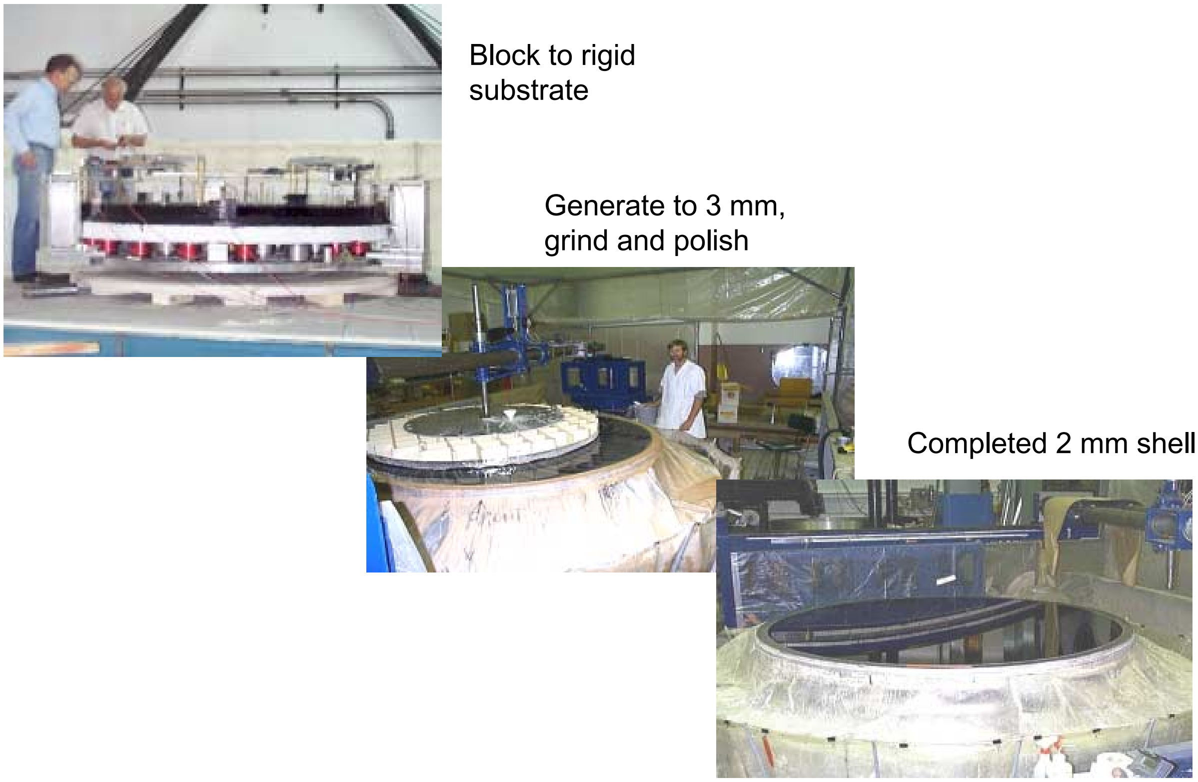

Figure 7. Fabrication of the 2-m diameter glass shell for the NGST Mirror System Demonstrator.

The convex side of the 2.2-m blank was then generated and polished spherical. The surface is the back of the completed facesheet, where the attachments are bonded. Then this blank, about 35 mm thick, was blocked to a rigid substrate using pitch. The blank was held in an oven by a distributed support, while the liquid pitch layer was slowly squeezed out to its final thickness of 0.75 mm. After a slow cooling, the blank was rigidly bonded to the thick blocking body.

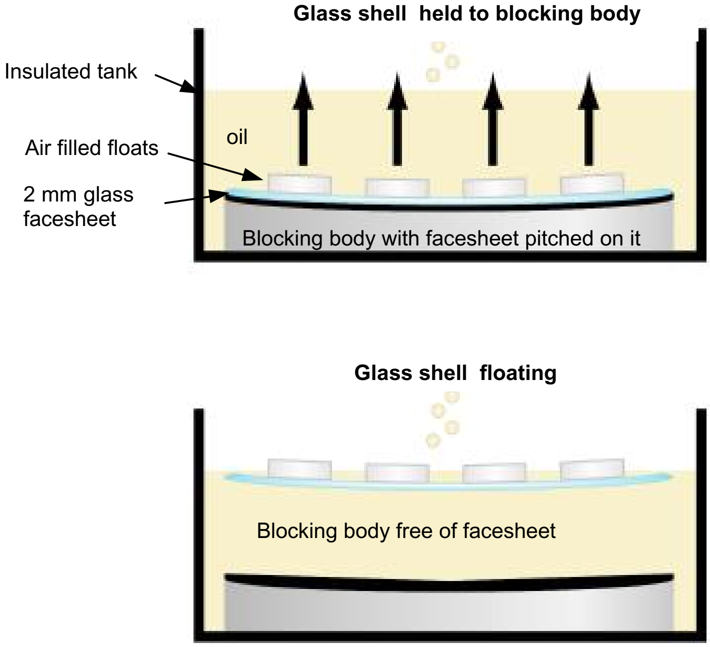

Figure 8. The completed shell was separated from the blocking body in a bath of hot oil using buoyant forces.

After blocking, the concave surface was generated with abrasive diamond wheels, leaving a 3 mm thick shell still bonded to the blocking body. This was then ground to a 2 mm final thickness and polished using conventional methods to a surface quality of about 1 wave rms. These operations are shown in Figure 7. The low order shape will be controlled by the actuators ultimately. The 2.2-m circular facesheet was then cut using a diamond saw into a hexagonal shape, 2 meters corner to corner.

The finished glass shell was separated from the blocking body by placing the assembly in a bath of hot oil and using buoyant forces to provide the separation forces, as shown in Fig. 8. Eighteen cylindrical floats were attached to the glass surface using RTV adhesive. The entire assembly was then placed in a 10-foot insulated tank which was filled with oil and heated to 250° F, shown in Fig. 9. Trim weights were placed on the floats to maintain a net upward buoyant force of 6.75 lbs at 250° F. The weights were trimmed as the facesheet started to lift. It took about 12 hours to heat up, 6 hours to float off, and 12 hours to cool back down.

After cooling, the glass was lifted out of the oil using an 18-point whiffle tree, Figures 10 and 11. The glass was cleaned with spray degreaser and placed on a transfer mechanism that matched the 18 lift points, Figures 12, 13, 14. The floats were then removed from the concave surface, and the glass was carefully cleaned, Fig. 15.

At this point, the glass shell rested on 18 points with the concave optical side face up. For the next operation, we attached the support hardware onto the rear, convex side. We used a full-size vacuum tool to handle the facesheet as we flipped it over. The tool, shown in Fig. 16, has a rubber interface with a convex surface that was replicated from the original concave surface of the shell. Channels were cut in the rubber surface, and hoses were inserted to distribute the vacuum. To lift the glass shell, this tool was lowered onto the facesheet and attached by vacuum. Then the tool was lifted, removing the glass from the 18 point support, and set onto a cart that has trunnions for flipping and wheels for transfer. The cart and facesheet assembly was moved to a clean room, Fig. 17, where the attachment hardware was bonded to the back of the facesheet. The vacuum fixture supported the facesheet during the bonding process.

Figure 9. The blocking body with attached facesheet is submerged in a heated oil bath. The floats, which are attached to the facesheet are visible near the surface.

Figure 10. After floating free, the facesheet is lifted from the oil using a whiffle tree attachment to the floats. It is tilted to allow the oil to flow out.

Figure 11. The deblocked facesheet was lifted from the oil bath with an overhead crane.

Figure 12. The oil was washed off the glass.

Figure 13. The completed facesheet, hanging from its whiffle tree.

Figure 14. The facesheet was set down onto another whiffle tree.

Figure 15. Completed 2 mm thick, 2-m hexagonal facesheet for the NMSD mirror

Figure 16. Vacuum support tool and handling cart

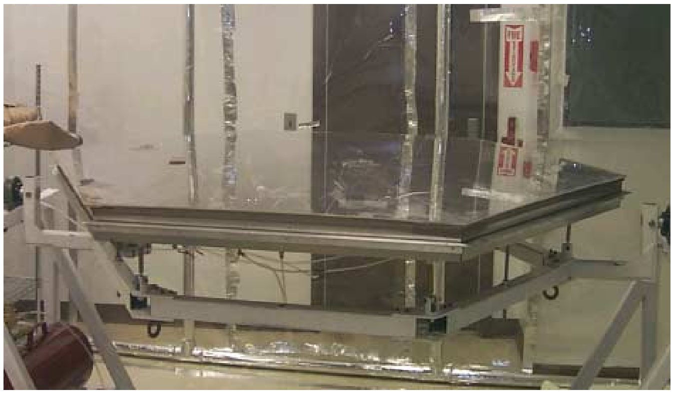

Figure 17. NMSD glass shell resting on vacuum support tool.

The glass pucks were bonded to the convex side of the shell using 12 µm thick 1564 urethane adhesive from PRC. This bond thickness was controlled by mixing 0.5 w% sieved Al_2O_3 microgrit into the adhesive. The bond area was maintained by carefully metering the adhesive into 0.4 mm^3 droplets. The liquid adhesive was forced through a fine bore needle and the droplet size was monitored optically. Figure 18 shows this process and Fig. 19 shows the surface with pucks and some loadspreaders.

Figure 18. The adhesive was metered into 0.4 mm^3 droplets using a fine bore needle and optical metrology.

Figure 19. NMSD glass with pucks, some sub-loadspreaders, and gluing jigs.

The sub-loadspreaders put in place and the glass caps were bonded onto the pucks using the same procedure as the puck bonding, although the tolerance were not so tight. Figures 19 and 20 show the glass with pucks and sub-loadspreaders. The hardware has undergone proof testing at 3 times the nominal load. Each puck was pulled in 1.45 lbs in shear and each sub-loadspreader was pulled 1.24 lbs in tension.

The sub-loadspreaders are captured by the glass caps bonded to the buttons, but are not initially constrained in position. This constraint is supplied by a bridge that is bonded to the sub-loadspreader that contact the top of the cap. This contact is maintained by a preload of about 0.03 pounds applied through spring washers. The loadspreaders are attached to the sub-loadspreaders using small screws. The screw head is spherical and forms the bearing for the sub-loadspreader to loadspreader joint. This joint is preloaded to 0.16 pounds using a spring washer.

Figure 20. NMSD glass with pucks and sub-loadspreaders.

Figure 21. Attachment of loadspreader..

4. ACTUATORS

The actuators lie at the heart of the active mirror. The final shape of the optic is controlled by adjusting the actuators, so their operation is critical. The requirements for these devices are challenging. The actuators must be remotely controlled with 20 nm resolution, and they must weigh less than 50 grams, including cabling. They must use minimum power for operation and zero power to hold their shape. For NMSD, the actuators must work both at ambient temperatures and at the 35K operating temperature.

We have developed a new type of actuator for this program that achieves these goals. The actuator, shown in Fig. 22 uses an electromechanical drive to make 1.4 arcminute rotations of an 80 pitch screw in a fixed nut. The net effect is an advancement of the screw of 20 nm. The drive unit and the lubricants were chosen for operation at cryogenic temperatures as well as ambient. The actuators have demonstrated excellent performance in both environments, as seen in the data shown in Fig. 23. We have now built, tested and installed all 166 NMSD actuators, plus 20 spares.

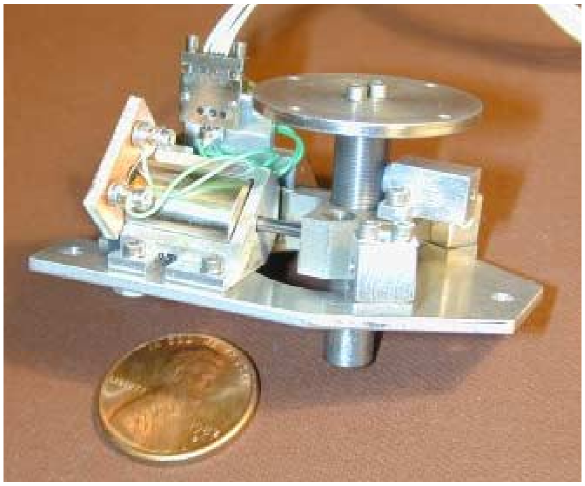

Figure 22. NMSD actuators weigh 44 grams.

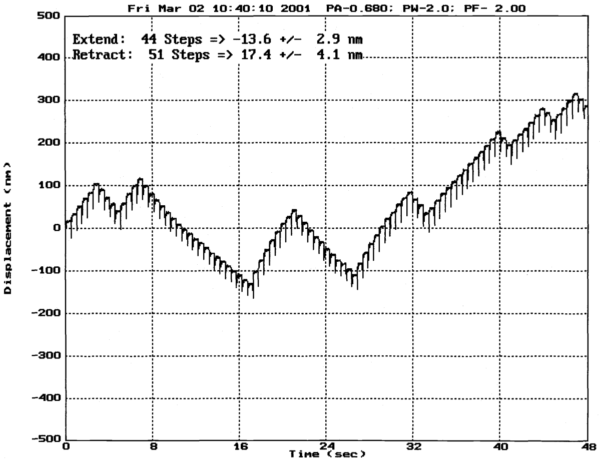

Figure 23. NMSD actuators achieve 20 nm steps at 35K.

Figure 24. 186 NMSD actuators were produced and tested.

5. SUPPORT STRUCTURE

The NMSD reaction structure is a lightweight, graphite reinforced composite assembly, fabricated by Composite Optics, Inc. (COI) in San Diego. Obtaining adequate stiffness and strength from this assembly using COI's technology has proven to be straightforward. There is considerable latitude in selecting the thermal strain characteristics for this reaction structure because the actuators will accommodate any distortion of the cell. We chose the system to have 0 CTE at the operating temperature. Figure 25 shows the assembly of the reaction structure at COI.

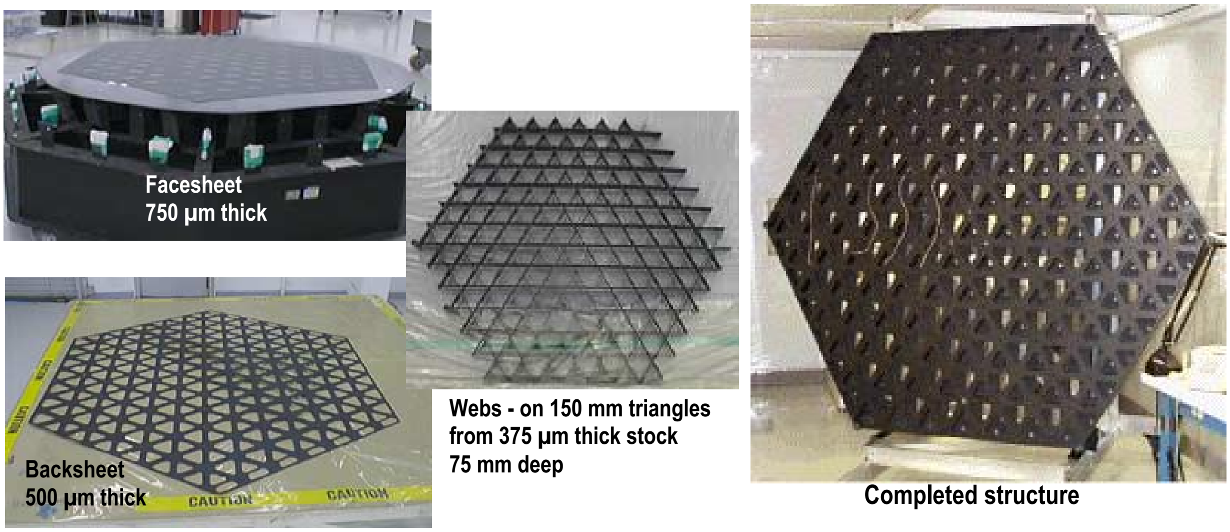

Figure 25. NMSD reaction structure, made from carbon fiber laminate by Composite Optics, Inc.

6. SYSTEM INTEGRATION AND TESTING

The NMSD is currently being prepared for its first testing as an active optical system. The actuators have been installed into the reaction structure and have been wired for power and control. (See Fig. 24.) The electronic system that drives the actuators has been fabricated and tested. The computer control of the actuators has been implemented and tested. In fact the same electronics and software were used for a different program.[5]

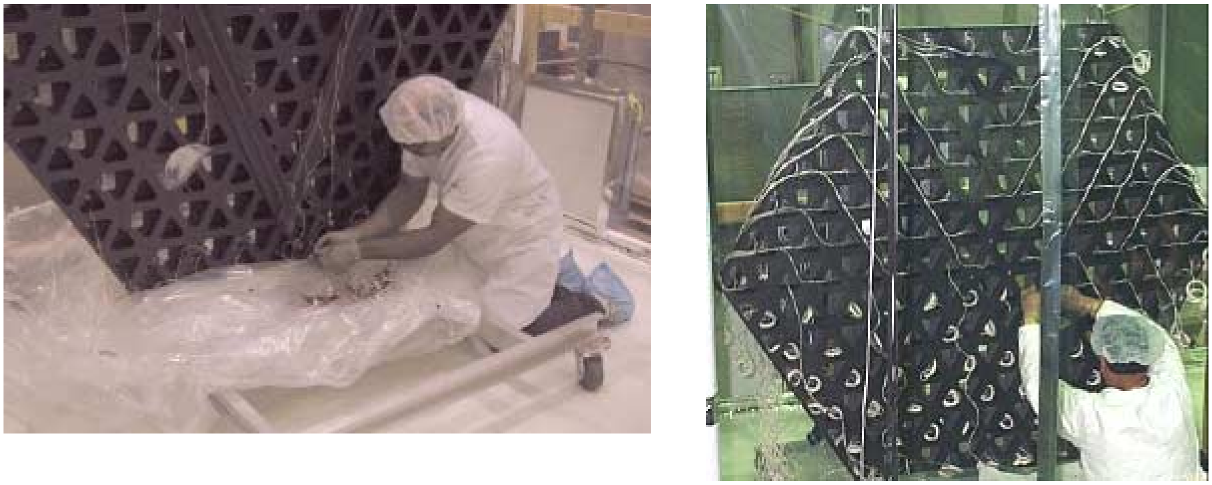

Figure 26. All 166 actuators have been installed into the reaction structure. The actuators are wired to 4 distribution boxes attached to the mirror support stand. These are connected to the electronic chassis by cables that will accommodate the cryogenic facility.

The glass facesheet is now being prepared for coating, then it will be integrated with the actuators. The assembly will set up under the large tower in the Optical Sciences Center and an interferometer will be used at the center of curvature to measure the shape.

7. CONCLUSION

The University of Arizona NGST Mirror System Demonstrator has nearly been completed. We look forward to the ambient temperature system testing at the University of Arizona and cryogenic testing at Marshall Space Flight Center.[6]

ACKNOWLEDGMENTS

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