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Abstract. Traditional mirror manufacturing, particularly for astronomical purposes, requires substantial lead time, due to the nature of the materials and the grinding/polishing process. We propose a new technique for rapid, low-cost production of large, lightweight precision optics by fusing several technologies which in combination we call frozen membrane mirror technology (FMMT). FMMT combines well-understood subsystem technologies, including electrostatic control of membrane mirrors, adaptive optics, wavefront sensing and control, and inflatable structures technology to shorten production time. The basic technique is to control the surface of a reflective coated membrane mirror with electrostatic actuation and wavefront sensor feedback and freeze the membrane shape. We discuss the details of the concept and present results of early lab testing. We focus on the optical regime, but this technology has applicability from the microwave to x-ray spectral bands. Starting with a flexible membrane mirror, one can envision techniques for deployment of large apertures in space. [DOI: 10.1117/1.OE.52.9.091810]

Subject terms: membrane mirrors; large optics; controlled optics; space-based telescopes.

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1 Introduction

The needs of the astronomy and defense communities for higher-resolution imaging and more signal collection capability have driven increases in telescope aperture sizes, optical surface quality requirements, and system alignment tolerances. Since primary mirrors are the fundamental enabling technology to realize these new systems, much attention has been directed toward evaluation of different manufacturing methodologies, the associated material technologies, and combinations of multiple subsystem technologies.[1] The need for low-cost precision optical manufacturing and/or deployment technologies extends across the spectrum from x-ray to microwave. Beyond the established grinding and polishing of rigid blanks, new technologies have been developed for advanced imaging systems such as:

1. segmented mirror telescopes that address the large-optics manufacturing issue and provide a means for deployment in space from limited launch shroud diameters;
2. replicated optics technologies using mandrels;
3. active optics with either embedded actuation elements or proximity actuation using electrostatic or magnetic fields;
4. large transmissive diffractive optical membranes such as the MOIRE[2] program sponsored by DARPA;
5. synthesized or sparse apertures;
6. new system approaches that combine several technologies, such as the nanolaminate construction formed on mandrels with embedded solid-state actuators.

This paper discusses an approach to the mirror manufacturing process,[3] called frozen membrane mirror technology (FMMT), which shows promise for enabling the rapid production of low-cost, large precision optics and increasing the viability of other competing technologies. FMMT falls under the last category in the above list as a new system approach to mirror manufacturing.

FMMT takes a very different approach to the mirror manufacturing process. During the mirror formation process, electrostatic actuators controlled by feedback from a wavefront sensor shape the membrane into a precisely defined surface. The mirror figure, described by the design optical prescription, is generated by commands loaded into the wavefront sensing and control (WFS&C) software. A fluid matrix is applied to the back side of a rim-mounted membrane and allowed to harden (or freeze) while the WFS&C system maintains the desired figure. When fully cured, the mirror can be removed from the facility for further testing and integration into the telescope. The process simultaneously manufactures the mirror and provides detailed surface figure measurements often requiring a separate test setup. The main virtue of this process is that it is very fast—a high-precision mirror can be fabricated in days, not in months or a year. As a result, the optical surface of the primary mirror costs significantly less than those made by other technologies. The schedule and cost advantages ripple through the system, allowing a larger aperture to be made for a given cost or a similar aperture size to be made at a lower cost.

The FMMT manufacturing process has three fundamental attributes that differ with the traditional grinding and polishing process. First, it inverts the methodology of obtaining a figure by grinding and then polishing to obtain a high surface quality. It starts with a precoated and tensioned membrane exhibiting high surface quality, which is then shaped with a feedback control system. This opens the possibility for membrane deployment in space with WFS&C substituted for precision deployment mechanisms. We have done some preliminary work on deployable versions that can support future large optical telescopes and very large reflectors for the microwave antennas. Second, those both traditional grinding/polishing processes and electrostatic actuation are localized (derivative actuation), the pulldown and tensioning of the membrane is a global or integrative process that inherently forms a smooth surface. Finally, the manufacturing process is very adaptive to changes in prescription, limited only by the boundary conditions formed by the membrane mounting surface and membrane stresses. The adaptive nature of the manufacturing process suggests that both segmented optics production and generation of the precision mandrels used for replicated optics are viable applications for the FMMT process. Segmented optical elements are typically generated from the figure specification of a parent conic, but each individual ring segment has a different prescription. For the FMMT approach, this translates into a set of different figure commands and solving the edge mounting geometry problem. With recent discussion of in-space deployment, assembly,[4] and manufacturing[5] of large telescopes, the FMMT process is a viable candidate for enabling the production of large telescopes in space. This is in part because the precision membrane material is deployable and transportable in a rolled form. The same FMMT manufacturing facility can be configured in software to adaptively manufacture a different optical figure and even off-axis optics.

In Sec. 2, we describe this manufacturing approach in detail, emphasizing the previously developed subsystem technologies that feed into the FMMT concept. FMMT is shown to be a natural evolution of several existing technologies combined together as a system. In Sec. 3, some initial experimental results are provided that show the ability to manufacture membrane mirrors with a ~20-Å surface roughness. In Sec. 4, we discuss system modeling and the multidisciplinary nature required to represent the complicated physics of FMMT during the mirror formation process. In Sec. 5, we discuss the further work needed to make this concept viable for ground and space applications. Although we believe this technology can impact deployable microwave systems and possibly provide a path for grazing incident x-ray mirrors, we focus the discussion on production of large mirrors in the optical wavelengths.

2 Description of the Technology

FMMT is a directed technique of a more general capability for rapid production of precision surfaces called frozen surface technology.[3] It is a fusion of several previously developed technologies: high-optical-quality membranes from space-qualified materials,[6] electrostatic control of membrane mirrors (ECMM), adaptive optics and WS&C, and ultra-lightweight (Gossamer) structures.[6] We will describe the overall process and then discuss the individual subsystem technologies that support FMMT.

As shown in Fig. 1, the mirror surface is measured by a wavefront sensor. This provides a feedback signal to the controller, which, when summed with figure command, generates an array of voltage commands. Electrostatic control of the metalized membrane surface is achieved by controlled charging of the patch actuator array etched on to a rigid control surface or shell structure behind the membrane.[7] These charged actuator pads form an electrostatic attractive force through a small gap with the metalized membrane surface, so they do not actually contact the membrane. The downward pressure on the membrane is directly proportional to the voltage level and the permittivity of the gap and inversely proportional to the control surface to membrane gap squared. This attraction causes an overall increase in membrane tension, thereby correcting any local surface deviations from a commanded surface profile. The number of actuation elements required for a membrane mirror is related to the global figure quality required. The mirror surface obtained is ultimately limited by the membrane surface roughness, which is shown to be several nanometers. Because the front surface is controlled, membrane thickness variations at scales larger than the actuation resolution scale should be minimized; this remains to be verified.

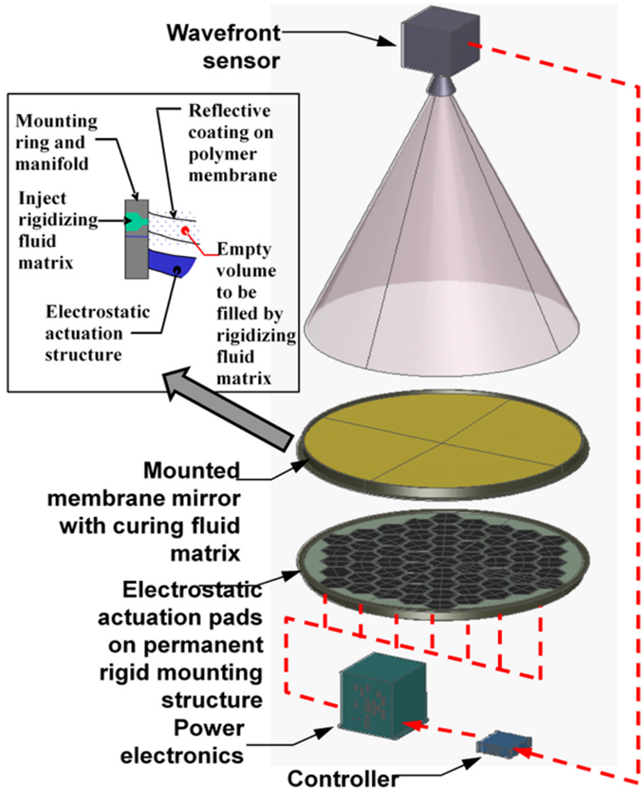

Fig. 1 Conceptual diagram of the FMMT process for producing a rigidized membrane mirror.

To freeze the controlled membrane figure, a curable fluid matrix is injected into a sealed chamber behind the membrane. Active control is maintained as the injected fluid cures at room temperature, adhering to and thereby freezing the mirror surface (hence the terminology "FMMT"). Because the surface is constantly monitored by a wavefront sensor, the error or feedback signal automatically adjusts to changes in capacitance with fluid injection or orthotropic membrane modulus properties, and so the quality of control is not affected. Note that we are losing controllability of the surface as the fluid solidifies, but simultaneously the tension force in the membrane is increasingly being opposed by the curing fluid, rather than the electrostatic force. The electrostatic power is turned off after the mirror figure stabilizes and the composite structure completely cures. Afterward, the rigidized membrane can be removed from the manufacturing facility for environmental testing and integration into the telescope assembly. The WFS and actuation system will not be part of the system for space operation unless a deployable version is developed.

There are many variations on the approach described above. The schematic does not include a central hole, as would be expected with a Cassegrain design. This feature can be included but was not for illustrative purposes. It is also possible to repeat this process to build up multiple layers or, with the right tooling, to form a complex shape with an egg crate architecture. Some relaxation would be expected, and this will need to be precomputed, as is done in the stress polishing process of standard mirror blanks.

2.1 *Membrane and Mounting Technology*

As described in several technical papers, there has been rapid development over the last 15 years in high-quality membrane materials for optical elements. Pellicle membrane elements have been used for years in optical elements such as beam splitters. For space-based operation, the focus has been on custom formulations of polyimide polymers. Polyimide materials offers many advantages, including the recently demonstrated capability either to have a coefficient of thermal expansion (CTE) near zero[8] or to match its polymer CTE to that of the rim mounting structure.[9,10] Polyimide polymers are well characterized in a space environment (thermal management and solar reflectors), and with coatings applied, they are among the better polymers in terms of radiation and atomic oxygen resistance. Special coatings can be applied to enhance the adhesion properties for the fluid matrix. The membrane materials can be obtained precoated with aluminum, but for UV applications, an additional coating of MgF_2 is required to retain high reflectivity. One issue is whether to precoat the reflective surface (which will introduce stresses into the coatings during manufacturing) or coat afterward (which makes surface control more challenging). Two vendors currently producing high-quality polyimide membrane materials are Nexolve and UBE Industries.

2.2 *Electrostatic Control*

ECMM is a well-developed technology, having been investigated and experimentally validated in the late 1970s and early 1980s at Massachusetts Institute of Technology[11,12] and other places.[13,14] The ECMM is characterized by nonlinear multivariable equations, and Lang[12] noted that feedback control can introduce system instabilities. Nonetheless, Lang was able to demonstrate stable control on a one-meter prototype. One of the key issues is the electrostatic actuators—how much voltage is required, how many actuators are needed, and what is the additional effect on control with the addition of a fluid matrix. The number of actuators, N, is related to the surface tolerance required, ε, the diameter of the mirror, D, and the focal ratio (focus/diameter $= \delta$) of the mirror. If we apply bias offset voltage on a parabolic control surface, the relationship, as derived by Lang[12] for a parabola, can be used to approximate the number of discrete actuator pads.

$$D/\varepsilon \approx 93\delta N \cdot \left| 3.3\sqrt{N\delta}\sin h\left(\sqrt{3.9N\delta/D}\right) - \cos h\left(\sqrt{3.9N\delta/D}\right)\right|. \tag{1}$$

As an example, for a 4-m membrane mirror and a focal ratio of 1, we require 50 electrostatic actuator pads to achieve a 71-nm root mean square (rms) surface quality. This is under ideal conditions and assumes an equipotential bias voltage condition. In addition, the membrane and reflective coating stress levels would need to be evaluated. As we deviate from these ideal conditions, a higher-density actuation array will be required. However, the addition of a fluid behind the membrane has many benefits over the standard ECMM approach. It greatly increases the membrane structural damping, thereby decreasing both the control loop bandwidth and the sample rate requirements of the wavefront feedback sensor. Because the dielectric constant is much higher with the fluid matrix present, voltage levels are decreased for the same force field. Finally, it distributes the force on the membrane surface, requiring fewer electrostatic actuators. The effect of changing fluid matrix properties during curing has yet to be evaluated analytically.

The other aspect of the electrostatic actuation is the use of WFS&C. Commercially available wavefront sensors can measure the figure down to small fractions of a wavelength of visible light. However, the WFS must typically measure the surface at a rate of 10× to 20× the closed-loop bandwidth to maintain loop stability due to phase delays. Therefore, additional damping is also important for reducing the demands on the WFS sample rate. The controller design can be implemented with field programmable gate arrays (FPGAs), adding tremendous flexibility for control design. Figure 2 shows a small testbed from early testing of the James Webb Space Telescope, which can be configured for testing a 1-m mirror. A wavefront control sensor approach to measuring the membrane and generating a feedback control signal is also shown. Ball has additional facilities to accommodate the testing of larger optics. In the configuration shown, the membrane reflective surface can be monitored for wavefront quality using an interferometer capable of short integration times. A polarizing beam splitter splits the outgoing source laser from the aberrated return beam to the interferometer, allowing wavefront errors to be computed. These signals need to be processed to generate the global wavefront error, and then the signals must be partitioned and converted to an appropriate voltage for each electrostatic actuation pad. To take advantage of the adaptive figuring capability, the collimating lens or assembly would need to have autofocus capability.

2.3 *Fluid Matrix*

The two areas of consideration are how to introduce the fluid matrix material and what properties are desirable for the fluid matrix. The simplest introduction method is simply to pour the fluid matrix on to the backside of the membrane and then seal the surface and invert. This approach, although simple, was found to introduce imperfections in the rigidized membrane due to entrapped air. The other two approaches, shown in Fig. 3, rely on injecting the fluid matrix and spraying it into the sealed chamber. These approaches also have

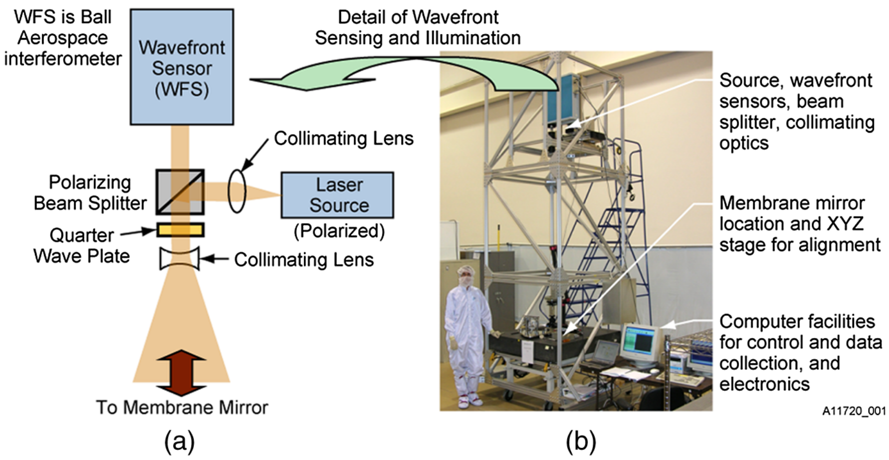

Fig. 2 Wavefront sensor configuration (a) and testbed figuration (b) for 1-m scale testing.

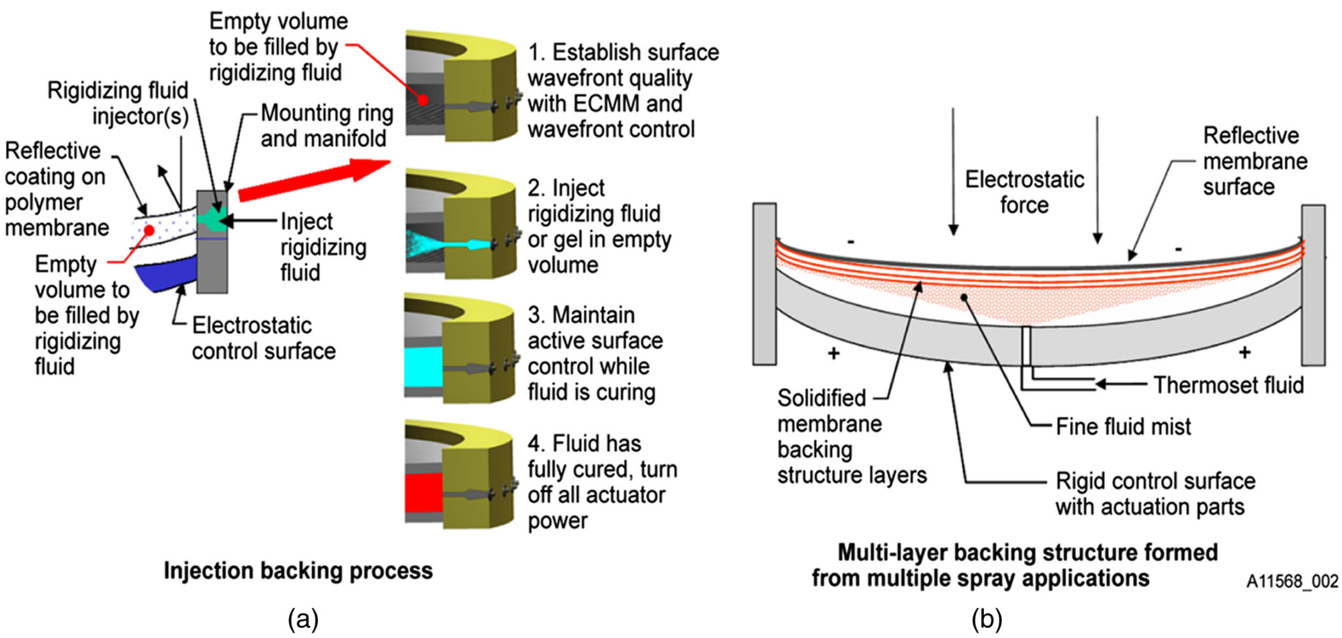

Fig. 3 Two concepts evaluated for rigidizing the membrane mirror with a curing fluid.

engineering issues to be resolved, with a main driver being the fluid matrix viscosity. Commercial equipment exists for both approaches in the molding industry, but differences in pressure and temperatures need to be part of the evaluation process. The spray approach has several advantages. It is easier to build up one layer at a time, giving each layer customized properties for optimizing the overall composite mirror structure. A combination of both approaches may provide the optimal structure – a thin rigidized membrane is initially produced, followed by formation of a composite backing structure for enhancing stiffness. For example, a curing fluid can be injected into a material such as a Kevlar weave structure that is in the reservoir before it is filled.

The important properties for materials in a rigidizing fluid matrix are low shrinkage, compatibility with the electrostatic actuators, a convenient curing method, bonding with the membrane, thermal stability with the support structure after curing, and a high specific modulus (high stiffness, low mass). Initial research on suitable materials has discovered that, in many curing materials, a high percentage of the shrinkage occurs early in the cure cycle before it has stiffened significantly. This is an advantage for control of the surface against compressive forces caused by shrinkage. Any dielectric material will be compatible with the electrostatic actuators and will enhance their performance. Likewise, conductive materials are prohibited in the path between the actuator pad surface and the membrane surface. The simplest material is a high-quality epoxy, but epoxy/composite fibers are better at achieving high stiffness and low CTE.

3 Experimental Results

It was decided to focus internal research and development (IR&D) on the membrane behavior as the fluid cured while the membrane was under tension control. Specific questions to be addressed were:

1. At what size scale does surface wrinkling occur?
2. How large are the wrinkles?

3. How should the fluid be introduced?
4. What's the best way to mount the membrane to the rim?
5. What surface roughness is achievable?
6. How does the surface change with time as the membrane is pulled down?
7. How does one incorporate all the physics into a model and then validate it with testing?

Not all goals could be accomplished with the funding available, so some questions were only partially answered. One decision made early was to use the Upilex-S polyimide made by UBE Industries, rather than the polyimide membranes from Nexolve, since the cost differential was more than an order of magnitude. For applications involving a path to space, the cost of Nexolve polyimide membrane is a small factor, and this would be considered the prime candidate material. The most important result from testing was verifying that the curing fluid/membrane interface did not produce micro-wrinkles that cannot be removed. The global figure and mid-frequency errors are controlled by the electrostatic actuator density and the pad design. The complex interactions between the fluid matrix and the membrane mechanics were considered the most difficult aspect to verify through modeling alone, and this was considered the No. 1 output of the testing. Therefore, two types of surface metrology were incorporated into the testing: coarse three-dimensional surface tracking while the membrane was being pulled down and the fluid was curing, and small-scale high-fidelity surface measurement after completion. The system modeling, discussed in Sec. 4, was regrettably deferred to a future effort.

The test setup involved mounting an Upilex-S polyimide membrane 180 mm in diameter and 51 μm thick on a rigid aluminum frame and evacuating the backside. Upilex has a linear thermal coefficient of expansion of 16 ppm/K, slightly less than the mounting frame. The vacuum emulated the actuation process, although no usable optical figure is obtained, due to residual higher-order surface error terms (dominated by spherical aberration). Unlike electrostatic actuation, vacuum actuation does not allow global figure control. However, it permitted fine-scale measurements confirming that the fluid matrix curing was compatible with a polyimide membrane as an optical element, demonstrated excellent cohesion, and provided a methodology for membrane mounting and adjustable pretensioning. The membrane mounting process and mount geometry establish the boundary conditions and are key to minimizing uneven stresses in the membrane and maintaining the vacuum and fluid seals. To minimize uneven strain into the membrane and vary the membrane tension, we borrowed a concept developed at the air force research laboratory[15] that involves stretching the membrane over a raised ring inside the main mounting ring. This allows radial self-equilibration of the strains, since the membrane is free to slide. Variable tension was applied to the membrane using a small ring channel that could be evacuated in a controlled manner.

We evaluated a range of fluid matrix materials before settling on two candidates for further testing. To set a baseline, the initial testing was conducted with Epotek 301 epoxy. Although the tensile strength and thermoelastic properties are nonideal compared to the desirable properties previously listed, they would be used to set a baseline and help define the research on candidate fluid matrix materials. The other material we investigated further was an epoxy/silicon carbide whisker matrix. Test strips of the epoxy and the epoxy/silicon carbide whisker matrix, as shown in Fig. 4, were tested for adhesion to the polyimide before any mirror testing was conducted. To enhance adhesion, the Upilex membrane was purchased with an optional surface treatment.

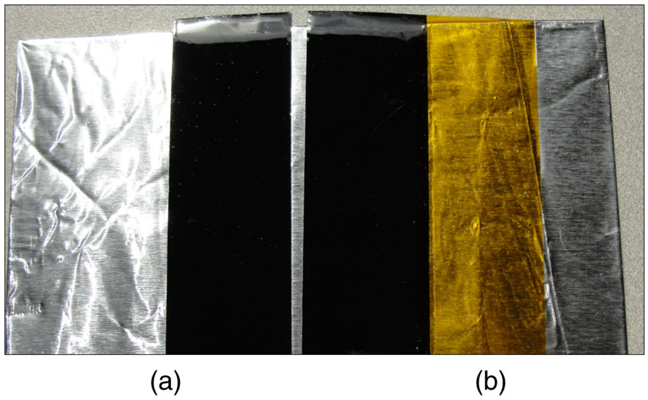

Fig. 4 Epoxy/silicon carbide (a) and epoxy only (b) deposited on polyimide for adhesion testing.

Because the modeling portion of the R&D was deferred, we needed some measure of test parameters for a starting point and future validation. One advantage of using vacuum actuation is that there are solutions to the membrane equation for deflection versus a uniform differential pressure. We start with the von Karman equation[7,16] for a thin circular plate,

$$\frac{1}{r}\frac{\mathrm{d}}{\mathrm{d}r}\left(rT_r\frac{\mathrm{d}w}{\mathrm{d}r}\right)+p(r)=0 \tag{2}$$

$$\frac{Eh}{2}\left(\frac{\mathrm{d}w}{\mathrm{d}r}\right)^2+r\frac{\mathrm{d}}{\mathrm{d}r}\frac{1}{r}\frac{\mathrm{d}}{\mathrm{d}r}(r^2T_r)=0, \tag{3}$$

where r is the radial coordinate of the membrane, h is the membrane thickness, w is the deformation of the membrane surface, T_r is the membrane tension, E is Young's modulus, and P is the differential pressure. The Hencky series solution,

$$W(r)=h^3\sqrt{\frac{ca^4p(1-\upsilon^2)}{Eh^2}/2(1-\upsilon^2)\left\{g(a)-\frac{r^2}{a^2}g\left(c\frac{r^2}{a^2}\right)\right\}}, \tag{4}$$

where a is the radius of the mirror, υ is Poisson's ratio, c is a constant given by

$$c=\frac{2(1-\upsilon)}{3-\upsilon}-\sum_{n=2}^{\infty}(b_nc^n), \tag{5}$$

and g is defined by

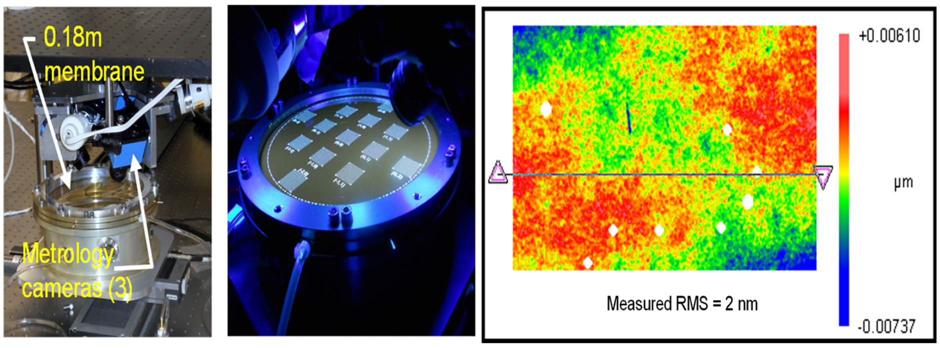

Fig. 5 Research done at Ball has demonstrated the ability to create a concave surface on a tensioned polyimide membrane then freeze the membrane with a rigidizing fluid. Left: The FMMT internal research and development membrane/fluid matrix testbed. Middle: mounted polyimide membrane under UV illumination for measuring surface targets. Right: surface measurement over 0.8 mm showing 2-nm rms surface quality after membrane is frozen, demonstrating that the FMMT process produces optical surfaces suitable for astronomical telescopes.

$$g(x) = 1 + \frac{1}{4}x + \frac{5}{36}x^2 + \frac{55}{576}x^3 + \frac{7}{96}x^4 + \frac{305}{3456}x^5 + \frac{51153}{1016064}x^6 + \ldots, \tag{6}$$

applies to a stress-free mounting configuration. The generalization to a prestressed membrane requires the modified Hencky–Campbell formulation laid out by Marker.[7]

These equations can then be used as a starting point for expected deflection, as long as the initial tension is not large.

For FMMT manufacturing, the interest is in figure control of the surface. For this experiment, we were interested in three-dimensional tracking of the membrane surface, so we applied a regular pattern on to the membrane surface and used three uniquely oriented cameras to track the dot pattern. It took 24 h from start to finish to produce a stabilized mirror for follow-up fine-scale measurements of the mirror surface. PhotoModeler software, in combination with 3D motion control of the cameras, enabled surface motion tracking to approximately 1 μm. We followed this up with a very high-resolution optical metrology system (Zygo profilometer) that measured subnanometer surface roughness. The test setup, the mounted membrane mirror with the applied patterns, and the resulting surface measurement are shown in Fig. 5. Ultraviolet ink was used for the dot patterns to increase the signal-to-noise ratio, which allowed us to get the micron-level resolution. The righthand figure shows that, over a 0.8-mm span, we have achieved an rms of ~20 Å. This measurement was repeated over different areas of the membrane, and the quadratic curvature terms were removed through curve fitting. The experiments proved that very high-quality surfaces can be produced in a short timeframe.

Unfortunately, the results from the larger-scale measurements using the three-camera metrology system are not available for this paper, because they will require further processing. We did not see evidence of thickness variations[15] in the surface measurements, and this may be due to the limited spatial scale of the Zygo measurement. Two-dimensional maps over an area of 0.72×0.54 mm also did not show the surface deviations expected from thickness variations. Additional testing will be required to fully understand the surface properties after curing.

4 Full System Modeling

The equations representing the complete FMMT manufacturing process are difficult to model, due to the complexity of multiple interacting fields, the nonlinear membrane structural behavior, the time-varying properties of the fluid matrix as it cures, and the multivariable control system. However, it is a necessary step to understand the scaling relationships from the subscale experiments, to size the mechanical components, and, most importantly, to generate a digital controller design for field programmable gate array implementation. The model is still in process, but the system model utilizes the COMSOL Multiphysics software environment to capture the interacting

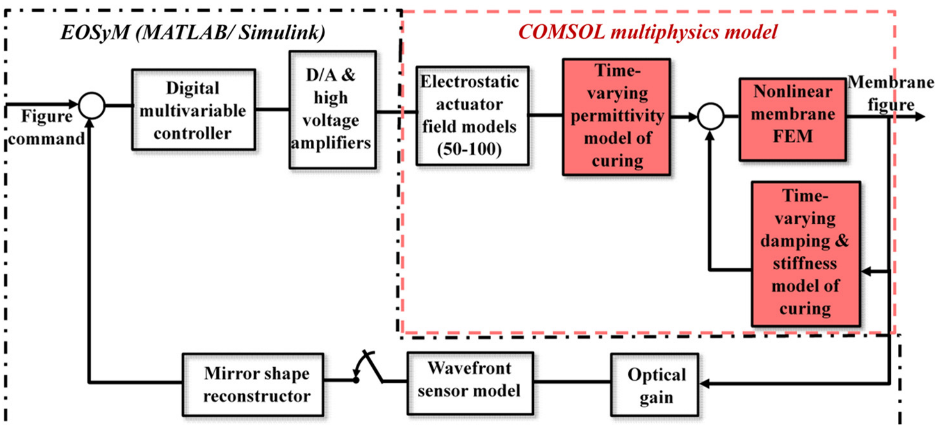

Fig. 6 FMMT coupled multivariable control system block diagram using COMSOL multiphysics and the EOSyM integrated modeling tools.

fields and nonlinear membrane structural behavior. We then interface our integrated modeling toolset, the end-to-end optical system modeling (EOSyM) tools, to capture the control system and optical wavefront properties. EOSyM is used extensively in support of the James Webb Space Telescope (JWST) program (called ITM for that program). EOSyM is built from the Matlab/Simulink toolset and readily interfaces with COMSOL. A representation of the coupled model is shown in the diagram of Fig. 6. For fluid modeling, we can borrow from the substantial work done in support of resin transfer molding.[17] Our intent is to publish a follow-on paper that discusses the modeling results.

5 Future Directions

This technology has applications for ground telescopes and space-based platforms. Further testing and development is necessary to ensure the long-term stability and to desensitize the mirror to changes in the thermal environment. There are several avenues for addressing these issues, including further work with fluid matrices that have low CTE and high specific strength properties. The specific strength is less of a concern, since additional stiffness can be designed into a backing structure. However, with all large optics, print-through of the supporting structure will need to be addressed. An additional consideration with most composites is water absorption and the associated dimensional changes that occur. Progress has been made in this area with the use of barrier films. For space applications, additional requirements occur, due to the launch environment, uneven thermal loading,[18] and the effect of high-energy particles on the mirror. Deployment in space is very difficult and costly, as evidenced by the price tag associated with the JWST. Deployment of a membrane is feasible, as was demonstrated by the NASA-sponsored Inflatable Antenna Experiment program.[19] However, attaining a precision figure in space after deployment is difficult without active control. With FMMT, the active components would need to be included to rigidize the mirror after deployment. The FMMT concept offers the potential for in-space fabrication in the future, perhaps as a facility on the space station. Once the technology has been proven and the membrane/fluid interaction and evolution during rigidization is understood, a mirror system could be launched that will be unfurled, surface controlled, and frozen in space, potentially changing the paradigm and limits for primary mirror size and therefore expanding the goals of the scientific community.

Finally, we have not discussed microwave, infrared, or x-ray opportunities, but the unique manufacturing process offers distinct advantages for manufacturing in each spectral region.

6 Conclusion

In this paper, we have presented a new methodology, FMMT, to mass-produce large precision optics. Initial testing indicates that surface roughness levels of ~20 Å can be achieved. The global figure is obtained through the use of electrostatic actuation with feedback from a wavefront sensor. We have calculated that, for a 4-m membrane mirror using a biased voltage or differential vacuum actuation, only 50 actuation pads are required under ideal geometry conditions to form a parabola. Actual numbers will require a complete multiphysics model to investigate many interacting effects. Finally, we have discussed briefly a wide range of applications and the key developments required for both ground and space operation.

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Mike Lieber is a principal system engineer at Ball Aerospace and the inventor of the FMMT approach presented in this paper. His main areas of expertise are in control systems and integrated modeling of complex optical systems. He is also taking a lead role in developing mission system modeling tools to support a broad range of programs. He developed the original integrated modeling tools used on JWST's wavefront control system and has applied these system tools to

interferometers, large ground and space telescopes, spectrometers and lidar systems. He was the program manager for the IRAD which did the developmental work on the FMMT.

Stephen Kendrick is a senior project engineer at Ball Aerospace and is their Technology Area Lead for Space Telescopes. He has been working with spaceborne optics for 40 years including star trackers and sensors, Hubble Space Telescope, Spitzer Space Telescope, James Webb Space Telescope, Terrestrial Planet Finder, JDEM, and several lightweight demonstration mirrors. In addition, he has been program manager for a number of deformable mirrors and IR low observable technology programs.

Sarah Lipscy is currently the chief scientist for the Ozone Mapping Profiler Suite (OMPS) at Ball Aerospace & Technologies Corp. In this role, she manages the performance requirements, including calibration, of the JPSS-1 instruments currently in test, responds to inquiries regarding the on-orbit performance of the NPP-OMPS, and interacts with the science community users of the OMPS data. As a systems engineer at Ball Aerospace, she has worked on the OMPS program for a total of 7 years and also on the ground calibration of the Operational Land Imager (OLI) for the Landsat Data Continuity Mission (LDCM). She received her PhD in astrophysics and astronomy at the University of California at Los Angeles (UCLA) where she studied the physics involved in the evolution of massive stars using observations from various ground based observatories including the Keck observatory and the Very Large Array radio observatory. Prior to beginning her PhD thesis work, she was involved in helioseismology projects using satellite data at UCLA and space weather projects using both ground and satellite observations at the University of Colorado—Boulder for her Master's and undergraduate theses', respectively.

Dennis Ebbets has 32 years of experience in space astronomy, including 28 years at Ball Aerospace. He has served as a calibration scientist, systems engineer and member of the Investigation Definition Teams for three science instruments for NASA's Hubble Space Telescope, and was Ball's project scientist during the development of the NGST/JWST mission concept. Dennis has been the Business Development Manager for astrophysics since 2005. An important part of his work is identifying and advocating for new technologies that may add value to future missions and instruments. He is a frequent speaker at public events, with HST, JWST, and Kepler being among the most popular topics.

Biographies and photographs of the other authors are not available.