JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 43, No. 1, January–February 2006

Gossamer Spacecraft: Recent Trends in Design, Analysis, Experimentation, and Control

Eric J. Ruggiero and Daniel J. Inman
Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061

Introduction

AN emerging interest in the gossamer spacecraft community is the development and design of membrane optics that meet the stringent surface quality requirement of spaceborne telescopes. Appropriately, the development of an ultralarge, multifunctional membrane optic is being tackled head on by multiple disciplines. Strides are being made in material science, engineered actuators and sensors, and modeling techniques that can handle the unique characteristics that make gossamer structures so fascinating as well as challenging.

Thorough reviews of gossamer spacecraft and related issues can be found in a few key sources. In 1995, Cassapakis and Thomas[1] provided a historical perspective on the development of inflated satellite technology. Their paper covers topics such as design variables for building large, inflated craft; thoughts on new deployment and rigidization techniques; multiple applications for large, inflated craft (such as satellites, space targets, decoys, and antennae); and most importantly, lessons learned from their research and areas of research most deserving of further attention. In 2001, Jenkins et al.[2] assembled a bound volume for AIAA that covers many facets of gossamer technology. The volume consists of 21 chapters devoted entirely to issues important to gossamer structures, like mechanics of membrane materials, fundamentals of membrane optics, modeling of deployment and rigidization methodologies, unique materials and their properties, and conceivable applications of ultralarge, ultralightweight craft.

As a follow-up to the 2001 AIAA volume, Wada and Lou[3] from the Jet Propulsion Laboratory (JPL) assembled a review of the JPL's preflight validation tests for gossamer structures. Wada and Lou discuss topics such as thermal creak response of deployable structures, zero-gravity deployment of an inflatable tube, and using modal tests to update finite element models of complex, inflatable structures. The authors address JPL's use of analytical as well as experimental techniques for some of their preflight validation procedures. In 2003, Ruggiero et al.[4] provided a literature review of inflated toroidal structures, focusing primarily on experimental modal analysis techniques of such structures using smart material actuators and sensors. Their review indicates some of the benefits of using smart materials (such as polyvinylidene fluoride, or PVDF, and piezocomposite fiber actuators), as well as some of the issues that must be addressed when using such testing methodologies.

Although these literature reviews are comprehensive, none of them addresses the specific issue of wrinkle elimination and membrane shape control in gossamer structures. Over the past five years, strides have been made in each of these research areas. It is the goal of this work to provide a useful summary of recent breakthroughs in gossamer technology, to address some of the issues currently facing gossamer structure design, and to suggest future research endeavors based on the excellent foundation already established. This paper will discuss some of the more recent developments and provide reference to some of the earlier groundwork that helped jumpstart gossamer spacecraft. Although not all references can be referred to in this work, the papers provided should help direct the search of interested engineers and scientists.

The outline of the present review is as follows. First, a general overview of recent trends in analysis, design, and experimentation with gossamer spacecraft will be presented. Then, a review

Eric J. Ruggiero received his Ph.D. from Virginia Polytechnic Institute and State University in Mechanical Engineering in 2005 and is currently a research engineer at GE Global Research (One Research Circle, Niskayuna, NY 12309). He is a National Science Foundation Graduate Research Fellow and a Virginia Space Grant Consortium Scholar. He has published 5 journal papers, 1 book chapter, and 14 conference proceedings in the area of gossamer spacecraft technology. He is a member of the AIAA, the American Society for Mechanical Engineers, the Gossamer Spacecraft Program Committee, and the National Society for Professional Engineers. He was the recipient of the 2004–2005 AIAA Adaptive Structures Graduate Student Award.

Daniel J. Inman received his Ph.D. from Michigan State University in Mechanical Engineering in 1980 and is the Director of the Center for Intelligent Material Systems and Structures and the G.R. Goodson Professor in the Department of Mechanical Engineering at Virginia Polytechnic Institute and State University. Since 1980, he has published 5 books (on vibration, control, statics, and dynamics), 8 software manuals, 20 book chapters, more than 175 journal papers, and 280 proceedings papers; given 27 keynote or plenary lectures; graduated 42 Ph.D. students; and supervised more than 60 M.S. degrees. He is a Fellow of the American Academy of Mechanics, the American Society of Mechanical Engineers (ASME), the International Institute of Acoustics and Vibration, and the AIAA. He is currently Technical Editor of the *Journal of Intelligent Material Systems and Structures* (1999–), Technical Editor of the *Shock and Vibration Digest* (1998–), and Technical Editor of the journal *Shock and Vibration* (1999–). He is a founding member of the ASME Adaptive Structures and Material Systems Technical Committee and the AIAA Adaptive Structures Technical Committee. He won the ASME Adaptive Structures Award in April 2000, the ASME/AIAA SDM Best Paper Award in April 2001, and the SPIE Smart Structures and Materials Life Time Achievement Award in March 2003.

Received 19 February 2004; revision received 9 December 2004; accepted for publication 13 December 2004.

of membrane mirror technology development and applications will follow. Next, research into the area of wrinkle computational and experimental analysis will be considered. Finally, recent developments in the area of gossamer spacecraft and membrane optics control system design will be reviewed. A summary of current trends and future directions will conclude the paper. A quick reference guide has been provided in the Appendix to direct interested researchers by topic headings.

Recent Trends in Designing and Analyzing Gossamer Spacecraft

While working for Astro Research Corporation in 1981, John Hedgepeth[5] prepared and submitted a contractor report for NASA Langley Research Center entitled, "Critical Design Requirements of Large Space Structures." In his report, Hedgepeth identified early on that "reliability and cost are important factors in a [spacecraft] design." As a consequence, Hedgepeth recognized that ground testing was the link between these two important design criteria because reliability is proven through preflight ground testing, and ground testing is a major source of recurring and nonrecurring costs. The report also points out that the two primary environmental loads for satellites are air drag and solar pressure. Most importantly, Hedgepeth[5] summarizes critical structural-controller interactions through a series of pertinent (yet rather simple in nature) set of equations that can be used as primary design guidelines. These back of the envelope calculations include, for example, calculating the effective stiffness of the control system, the control frequency bandwidth, and the allowable amount of surface distortion of an aperture as a function of mission parameters.

Since Hedgepeth's report in 1981, researchers have taken strides to establish satellite requirements for ultralarge, ultralightweight craft. In 2002, Davis and Agnes[6] quantified the magnitudes of different environmental disturbances bombarding gossamer spacecraft at varying orbital altitudes. The authors specifically calculated the effect of the gravity gradient, magnetic torque, solar radiation pressure, atmospheric drag, and thermal loads on the Inflated Antenna Experiment (launched in 1996). An interesting result of their analysis is that the effect of different loadings at varying orbital altitudes when plotted on a log–log plot has the same shape as a similar graphic for smaller satellites. The only difference between the two (large space structure compared to smaller satellite bus) is that the loading effects are (in general) two orders of magnitude larger for the bigger spacecraft bus. Considering the increased dimensions and distributed mass of the larger gossamer spacecraft buses, such a trend is expected and makes sense.

Elsewhere in the literature, some researchers have focused on understanding the nonlinear behavior of membrane optical elements and pressurized parabolic lenses. In 1997, Marker and Jenkins[7] investigated the influence of boundary conditions on the shape error in parabolic profile membranes. First, the authors develop the Hencky problem (the inflation of an initially flat circular membrane with clamped boundary conditions) and show the evolution of the governing equations of motion. Marker and Jenkins then develop a finite element model based on the Hencky model and perturb different sections of the boundary condition to analyze the consequences of boundary manipulation. The authors were able to demonstrate a 58% reduction in the surface error by perturbing three points along the boundary of the membrane. Their work points in the direction of active control for optical applications with membrane or gossamer-type systems—a necessity of future research endeavors.

There have been a number of recent advances in terms of optical-level membrane mirror design. deBlonk[8] recognizes that one of the daunting problems facing ultralarge spacecraft system and control design is the use of ultralarge, often cumbersome models. In his paper, deBlonk develops a model hierarchy to "assess the cumulative effect of modeling assumptions upon solution accuracy and precision."[8] In his approach, he uses geometrically exact model solutions as baseline models to interrogate his proposed modeling assessments. deBlonk explores many different types of modeling error. He found that, for the use of models in designing optical-quality membrane primary mirrors, there is some dependence of the modeling error on the type of geometry used, but for the most part, "pressure-type loads provide the most consistent correlation to error."[8] Most importantly, deBlonk's modeling techniques establish practical limits on loads in linear model applications. By understanding the load limits of a linear model, the designer can accurately predict the final shape of a membrane optical element with confidence and know when that confidence level will break down (as the structure enters into a nonlinear region of analysis). The only drawback to deBlonk's analysis is that it is based on finite difference methods that might not be able to handle material discontinuities or geometric complexities well if future studies using his proposed method are pursued.

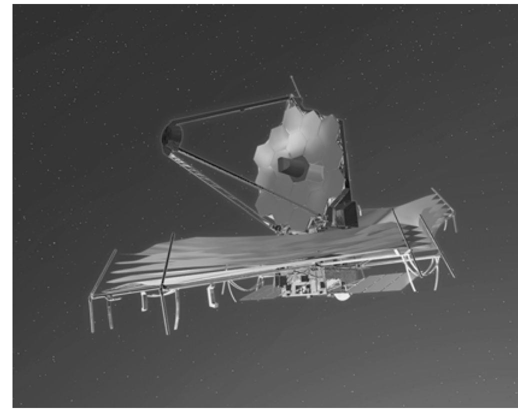


Fig. 1 Conceptual drawing of the JWST. Drawing courtesy of NASA/Northrop Grumman Space Technology.

Fang and Lou[9] provide a brief literature review on testing techniques for inflatable tubes and methods for predicting and analyzing wrinkles in inflated structures. The authors point out that although membranes cannot have an out-of-plane stiffness, a membrane under pretension does demonstrate an out-of-plane stiffness, commonly referred to as the differential stiffness. Interestingly, the differential stiffness is not constant under a given pretension if the membrane is subject to a localized compression. Under such a condition, wrinkles will redistribute the stresses, consequently altering the differential stiffness. The authors also provide a finite element analysis of the Next Generation Space Telescope, now known as the James Webber Space Telescope (JWST; Fig. 1). The authors used a finite element code to look at the dynamic properties of a 32.8×14.2 m Kapton membrane sunshield consisting of 40 membrane elements and 32 beam elements. The sunshield's first four resonant frequencies were identified at 0.23018, 0.32047, 0.44065, and 0.54409 Hz.

The extremely low structural frequencies found by Fang and Lou[9] are quite common in the structural analysis of gossamer spacecraft, making dynamic analysis and control extremely difficult. Such low frequencies call into question the very nature of the actuators and sensors that engineers can even consider when trying to design a gossamer spacecraft or space optic at the system level. In fact, the ultraflexible nature of gossamer craft is the main culprit as to why engineers have steered clear of such systems since the launching of the Echo satellites in the 1960s. However, advances in experimental analysis and analytical computations have led engineers to realistically consider gossamer technology as a viable system component. The next section looks at advancements made in the area of experimental analysis.

Recent Advances in Gossamer Spacecraft Experimental Analysis

Helping bridge the gap between engineering design and analysis is the art of experimentation. The testing of gossamer space structures is truly an art, as it requires technical prowess and engineering ingenuity to push the current boundaries of structural testing methodology.

In 2003, Pappa et al.[10] provided a summary of multiple facets of experimental analysis of gossamer space structures as performed by researchers at NASA Langley Research Center, Marshall Space Flight Center, and Goddard Space Flight Center. The authors explain the difficulties associated with performing more traditional modal tests on inflated, lightweight structures. The summary is quite valuable because it reflects actual experimental results developed from each of the NASA centers. The ultralightweight, ultraflexible nature of gossamer structures wreaks havoc with traditional dynamic testing techniques. For example, the use of an accelerometer as a dynamic sensor can add 50% more mass to the structure being tested, especially in the case of a solar sail. Further, the use of electromagnetic shakers to input a known disturbance into the system can puncture or tear the material being tested if the input energy is not properly distributed throughout the structure.

Pappa et al.[10] review some of the preliminary testing efforts for different gossamer-type components. Static tests for identifying structural properties have been performed on inflated, rigidized tubes. Dynamic tests using laser vibrometers, advanced photogrammetry, and electromechanical shakers have also been documented. Vibration control experiments have been implemented on cantilevered, rigidized tubes and demonstrate an effective increase in structural damping from 0.4 to 8% through the use of Macro-Fiber Composite (MFC®) actuators (a particular piezoelectric device developed initially at NASA Langley Research Center). Further research into the properties of the MFC actuator (shown in Fig. 2) can be found in Wilkie et al.[11] and Williams et al.[12]

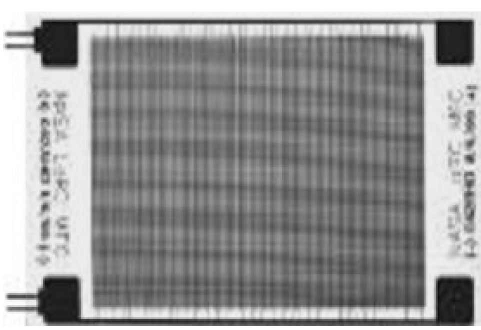


Fig. 2 Top view of the MFC actuator (86 × 57 mm).

Ruggiero et al.[13] developed an experimental modal analysis technique using multiple MFC sensors and actuators on an inflated torus. Their proposed MIMO (multi-input–multioutput) scheme was able to discern the resonant frequencies and associated damping ratios of the torus, as well as the significant out-of-plane mode shapes of the structure. Ruggiero et al.[14] and Ruggiero and Inman[15] experimentally compared the modal frequencies and damping ratios of an inflated torus with a membrane mirror glued to the interior of the ring (Fig. 3). As with Ruggiero et al.,[13] the authors used MFC devices as both sensors and actuators during the experiment. The authors found that MIMO testing techniques helped discern split modes in slightly asymmetric structures. (Split modes, or mode pairs, are nearly identical modes that occur at almost identical frequencies.) Also, the introduction of the membrane mirror to the interior of the torus significantly affected the response of the structure.

Understanding the interaction of the boundary and the interior mirror or antenna is a critical concern for those interested in successfully developing a fully deployable, ultralightweight space optic or radar system. For example, in the tests performed by Ruggiero et al.[14] and Ruggiero and Inman[15] a cavity had to be built around the inflated torus to protect the torus during dynamic testing from air currents generated by the laboratory's air conditioning. Such disturbances can wreak havoc with the structural response of the system. For gossamer technology to mature to a spaceworthy technology, such testing issues must be addressed.

Sodano et al.[16] investigated the use of multiple MFC devices for vibration control of an inflated torus (the same torus as in Ruggiero et al.[13]). In an experiment using two sensors and two actuators, the authors were able to reduce the vibratory levels of the primary resonant frequency by 70%. Sodano et al.[16] also looked at using the MFC device as part of a self-sensing circuit. Incorporating the MFC device into a self-sensing circuit, the authors were able to demonstrate a 90% vibratory reduction in the dynamics of a cantilevered beam. Novel actuator and sensor concepts for energy manipulation and storage must be pursued the enhance the multifunctionality of gossamer spacecraft.

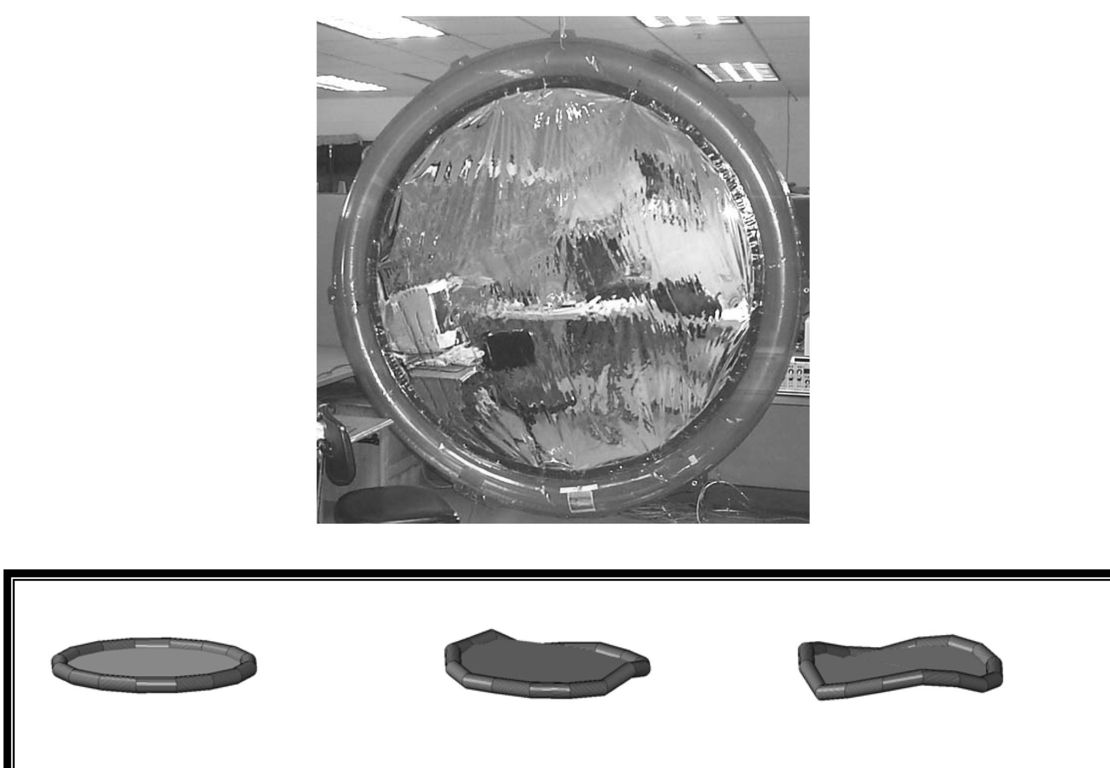


Fig. 3 Experimentally identified mode shapes of an inflated torus with attached membrane mirror (top). The torus is shown at rest (left) and vibrating at the first and second out-of-plane modes (middle and right).

Gaspar et al.[17] performed modal analysis tests on a 10-m-long, 7-μm-thick Mylar solar sail under vacuum conditions. The authors used two methods of excitation on the sail. In the first experiments, a magnetic, noncontact exciter was used to excite the out-of-plane modes of the solar sail. In a second round of experiments, an MFC bimorph was used to excite the out-of-plane modes of the sail. A laser vibrometer measured the frequency response of the structure undergoing a periodic chirp excitation signal. A key contribution stemming from this experimental work was the observation that the location of the actuators for system excitation was critical for achieving good test data. Finite element analyses of the solar sail were performed ahead of time to assess regions of maximum strain during dynamic testing. By placing the actuators at these regions, high-quality data measurement was successfully garnered. The authors' use of the finite element method for intelligent actuator placement highlights the benefits of proper preplanning for excellent testing setups.

Whites and Knowles[18] proposed in 2001 to create solar sails out of conductive carbon-fiber networks as opposed to continuous polymer sails made from Kapton or Mylar. The authors used computational electromagnetics to analyze the accelerations possible from their proposed solar sail and predict that accelerations on the order of 1 m/s^2 are possible. However, the authors' work was completely analytical, and no experimental results were provided. Further, the fabrication of precision conductive carbon-fiber networks at large scales is also an area of concern.

Cadogan et al.[19] summarized the results of two experimental technology demonstrators fabricated at ILC Dover, Inc. The first demonstrator was a 1-m X-band inflatable reflectarray consisting of a dual membrane assembly (a radiating patch layer and ground), three inflated struts, a support torus, and a feed horn torus (tying the struts to the support torus). The second technology demonstrator was a 3-m Ka-band reflectarray consisting of a horseshoe-shaped inflated boundary and tapered struts. The most significant results from the two demonstration prototypes were summarized in their report. First, the packing technique and deployment technique must be identified from the get go as they will drive the system design. Second, the membrane surfaces should never be folded; rolling should be used. And finally, the authors offer some testing tips such as developing a test fixture to hold the final assembly without disturbing it throughout testing, and they also suggest the use of constant force springs to apply tension to the membrane to isolate any dynamics from the inflatable frame.

Adetona et al.[20] performed experimental and finite element research on an inflatable hexapod structure with a tensioned membrane. The hexapod structure contains a 3.8-m-diam torus fabricated from 12 0.18-m-diam graphite–epoxy composite tubes. The interior membrane consisted of a Kapton backing with a vapor-deposited aluminized surface for reflectivity. The interface between the membrane and torus was a series of 12 cables 0.101 m long and 9.65×10^{-4} m in diameter. The prototype also contained three tapered struts (as shown in Fig. 4). Using a scanning laser vibrometer and a single-point laser vibrometer as velocity sensors and two electromagnetic shakers as force inputs, the frequency response funct ions of the hexapod structure were collected. Subsets of the collected data were first curve fitted using a matrix fraction description representation, and then models of the system were synthesized using the eigensystem realization algorithm.[21] The authors identified over 300 modes from their analysis, but only two of these experimentally identified frequencies coincided with the predicted structural response from a finite element model. As a result, the authors concluded that strut stiffness is significantly underpredicted and better testing techniques are necessary for identifying material properties. Experimental testing of inflated struts has been performed by Slade and Tinker.[22]

The inability of the finite element code to predict the dynamic response of the inflatable hexapod highlights the infancy of commercial finite element codes when applied to gossamer space structures. As will be discussed in the next section, the development of proper modeling elements, boundary conditions, and structural connections is another necessity in the future of gossamer structure research.

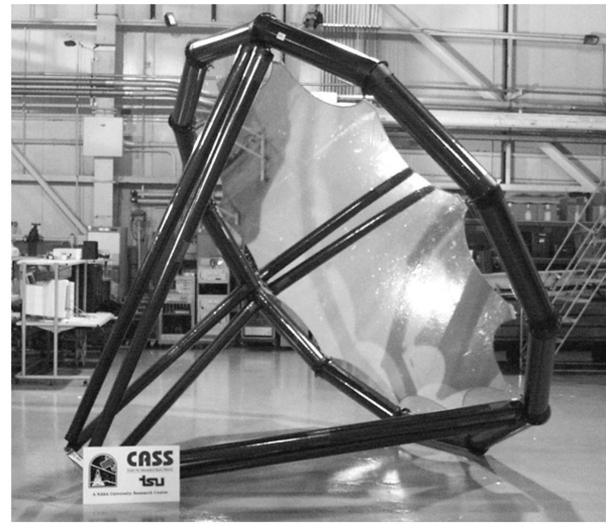
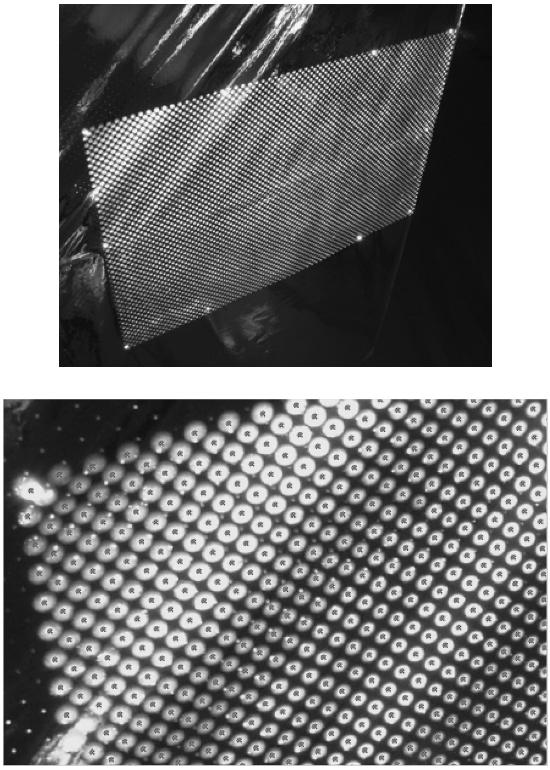


Fig. 4 Inflatable hexapod structure for dynamic analysis. Photo courtesy of NASA/L. Horta.

Recently, much research has also been performed in the area of photogrammetry—the science of calculating three-dimensional object coordinates from images—for deciphering the rich dynamics of gossamer structures. Photogrammetry and videogrammetry are terms that can be used interchangeably. Pappa et al.[23] describe a cookbook approach for using commercially available digital cameras to understand the dynamic response of numerous gossamer-type structures. The authors apply their techniques to a 5-m inflatable parabolic reflector, a 1-m flexible Fresnel lens, a 15-m inflated, rigidized tube, a 0.7-m oscillating Kapton membrane, a 3-m hexapod reflector (the same reflector analyzed by Adetona et al.[20]), a 4.5-m inflatable tripod, and three prototype solar sails. Pappa et al.[24] followed up their previous work by summarizing some of the lessons learned from their photogrammetry experiments. For example, the authors state that "retroreflective adhesive targets are generally not appropriate for measuring thin-film membranes whenever the targets must be removed afterwards."[24] Further, depending on the application, the setup of a photogrammetry experiment might be inappropriate, like trying to detect static wrinkles but having large targets sparsely located on a membrane structure relative to the wavelength of wrinkles present. A sample experimental setup is shown in Fig. 5. Johnston et al.[25] also used photogrammetry techniques to decipher the dynamics of a subscale sunshield membrane layer. The researchers found good agreement between their experimental results and their finite element analyses using the sunshield's dimensions, but they found that the finite element model could not predict the wrinkling details present in the experimental sunshield.

Pappa et al.[26] address the ability of certain photogrammetry methods to identify wrinkles in large membrane structures. Using a grid of about 5000 dots over a 0.5×1.0 m area, the researchers were able to correctly identify wrinkle amplitudes of 5-mm peak to valley with a photogrammetric measurement precision of approximately 25 micons. Blandinao et al.[27] provide a useful comparison between videogrammetry techniques and scanning laser vibrometry methods in identifying the modal characteristics of a large-scale gossamer craft. While yielding similar results, the authors point out the relatively inexpensive nature of the photogrammetric setup compared to the scanning laser vibrometer setup (which can cost from \$100,000 to \$200,000). These efforts were solidified in the results presented by Black and Pappa.[28] On a 2-m solar-sail sample, Black and Pappa[28] were able to demonstrate ± 0.02-mm accuracy (Fig. 6).

Dorrington et al.[29] have investigated laser-induced fluorescence photogrammetry to characterize the dynamic behavior of transparent and aluminized membrane structures. Through the use of laser-dye doped polymers, the authors demonstrate a noninvasive,



a)

b)

Fig. 5 Photogrammetry, a novel method for deciphering the rich dynamics of gossamer structures such as a solar sail: a) 2-m aluminized Kapton solar sail with applied spot targets for photogrammetric measurements and b) the upper-left corner of the solar sail magnified. Photos courtesy of NASA/R. Pappa.

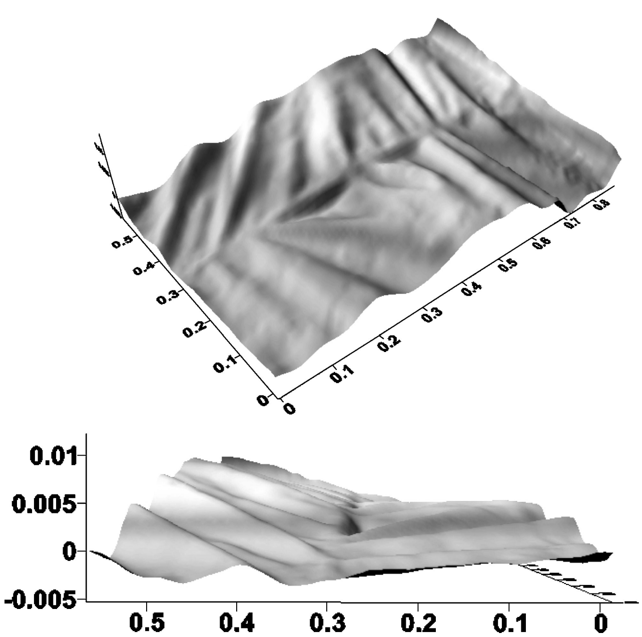


Fig. 6 Photogrammetry techniques can be used to measure the amplitude and frequency of wrinkles, as demonstrated by a 2-m aluminized solar-sail experimental analysis. Figure courtesy of NASA/R. Pappa.

noncontact testing technique that eliminates the need for retroreflective targets on the mass-sensitive membrane structure. The novel concept of laser-induced photogrammetry should be pursued with vigor in ensuing research projects.

Photogrammetry is an excellent fit with the overall nature of gossamer structures. It is an exciting combination of technology and engineering ingenuity. Such advances in testing continue to help bridge the gap between analysis and system design.

Surface accuracy and shape measurement of membrane surfaces has also been on the research frontier. In 2001, Tsunoda and Senbokuya[30] proposed a mesh-type aramid membrane based on a triaxially woven fabric. The authors built a steel-rim test stand and experimentally tested the surface distortion of a 2.0-cm circular sample of their proposed fabric. The authors found that the surface tension must exceed 130 N/m to hold the surface accuracy under 0.1 mm rms with 24 connection points around the steel rim. Measurements were taken of the fabric surface using a charge-coupled device laser displacement sensor. A second experiment was run using two inflated tori as the boundary around the rim of the mesh fabric, and similar results were found.

Also in 2001, Darooka and Jensen[31] looked at the design of inflatable and deployable space frames made from isogrid materials. Isogrid materials are composites that include a redundant mesh embedded within a durable substrate to create stronger, more durable truss or tubular component. Darooka and Jensen provide testing data demonstrating the superior strength to weight characteristics of isogrid components. Similarly, Cadogan et al.[32] looked into using shape memory composites for active elements in a gossamer spacecraft, including integrating them with isogrid booms for deployment. Although shape memory composites are heavily temperature dependent (and consequently not ideal for space flights), such experiments provide important insight into the physics and design of lightweight structures.

Flint and Glaese[33] were also interested in the surface accuracy and dynamic response of a stretched membrane sample. First, the authors provide a methodology for testing and characterizing the complex stiffness of certain gossamer materials, like Kapton. Over a bandwidth of 0–100 Hz, noticeable changes were shown in both the Young's modulus and the loss factor of different material samples (including Kapton and aluminized Mylar). Next, the authors dynamically tested an aluminum membrane sample held under tension and found that the first major membrane mode occurred at 72 Hz. However, when the membrane sample was switched to an optically transparent material and then a Kapton sample, the first resonant frequencies were found at 39.9 and 44.4 Hz, respectively. Finite element models were also generated and found decent correlation with the experimentally identified resonant frequencies. Flint and Glaese's work, as well as similar endeavors in the gossamer community, highlights the multidisciplinary approach that is necessary for success when working with these unique structures. In a similar fashion, Choi et al.[34] proposed integrating multifunctional circuitry into solar sails for enhanced power allocation and distribution, with the additional benefit of shape control and surface sensing.

Flint et al.[35] performed extended dynamic analyses of multiple membrane configurations. The authors used speakers to excite some of their samples, a scanning laser vibrometer to measure the dynamic response of each sample, and associated software to identify the resonant mode shapes of 0.5 and 1.0 m near net shape concentrators made from a variety of polyimide materials. Despite a number of difficulties encountered in trying to identify the modes of each concentrator, the authors devised a series of successful tests specific to each concentrator configuration. To test larger membrane samples, the membranes were mounted in a 1.0-m-diam ring. Although there were significant differences between the experimentally identified and analytically derived membrane frequencies, the authors did find excellent correlation in the analysis of their supporting ring structure. One trend demonstrated both experimentally and analytically is that the membrane resonant frequencies occurred in high densities over small frequency bandwidths. Dense modal behavior can lead to significant complications in control methodologies in the future, but is a typical characteristic of gossamer structures that must be addressed by current research efforts.

Bales[36] looked at a slightly different problem than Flint et al.[35] The authors tried to experimentally and analytically determine the dynamic response of membrane structures with discrete attachment points (as opposed to continuous boundary conditions). Testing was performed in a vacuum chamber. The authors observed that ambient temperature changes during testing caused different rates of thermally induced contraction in the membrane material, thus affecting the dynamic response of the membrane. Also, the amount of moisture absorbed by the membrane material had a significant effect on the dynamic response of the sample, as well. Consequently, the authors also demonstrated that proper boundary manipulation can ease the influence of these phenomena.

Despite these recent developments, there is still a lot to be learned in the area of membranes and membrane dynamics. Research has been conducted on how to properly account for some of the phenomena specific to the design of membrane-type structures, both in analysis as well as experimentation. Photogrammetry lends itself to be the testing medium of choice for gossamer components, as it is a noncontact, nonintrusive testing methodology capable of identifying static wrinkles and dynamic system response. Similarly, the integration of smart materials into the system design of gossamer components should also be pursued vigorously, as such integration can lead to advances in static shape control and dynamic vibration suppression of gossamer craft.

A more recent advancement in gossamer structure research is in the area of membrane optics. The next section will address the history, development, and design of membrane mirrors for future satellite applications.

Membrane Mirror Technology Development

Achieving ultralarge spacecraft with ultralow areal densities mandates the development of membrane mirrors and associated technology. The strict surface tolerance requirement, on the order of one-tenth of a wavelength of light, steers membrane mirror technology away from passive means. Membrane mirror shape control, vibration suppression, and wrinkle elimination will have to originate from an integrated, active monitoring and control system.

The proposition of using membranes as optical elements in telescopes and other imaging-type devices is not a new concept. In 1977, Grosso and Yellin[37] tested a titanium membrane optical element (with diameter of 50 mm and a thickness of 1.4 μm) actuated by 53 hexagonally shaped electrodes. The electrode actuators influenced the surface shape of the titanium membrane through electrostatic forces. A single electrode actuator was found to deflect the membrane element by 0.5 wave with less than 100 V applied. Grosso and Yellin analyzed the frequency response of their membrane mirror as well as the deflection of the surface under actuation. The authors found good agreement between their experimental results and their developed membrane equations.

The use of membrane mirrors in adaptive optic systems also started to take shape as digital processing capabilities grew in the 1980s and into the early 1990s. For example, Takami and Iye[38] described the research and development plans for constructing a Cassegrian adaptive optic based upon a deformable membrane mirror made of nitrocellulose. The adaptive optic system proposed was to be implemented on an 8-m-diam telescope system at Mauna Kea known as SUBARU. Two technologies were considered in the development of the adaptive optics system. The first technology considered was a bimorph mirror design, where "two thin plates of piezoelectric material [are] linked together and covered by [a] thin silicone plate that serves as the optical surface."[38] The second technology considered was a membrane mirror, "made of a very thin pellicle with high tension. The surface is coated with a metal (such as aluminum or gold) that acts as a mirror and an electrode."[38] Although research was performed on both technologies, the authors focused primarily on the membrane mirror because it inherently had a smooth, high surface quality unlike the bimorph mirror design. Similar to Grosso and Yellin,[37] Takami and Iye needed to use a vacuum window to keep the inside pressure on mirror at an appropriate level to adjust the membrane damping. The authors' tests included measuring the surface quality of the membrane optic statically as well as under actuation (by an electrostatic actuator). They looked at the frequency response, identified a strong resonant frequency of the membrane at 1.6 kHz, and were able to eliminate the resonance by adjusting the inner pressure on the membrane to 10 torr. The membrane mirror had a bandwidth of 3.3 kHz. Nearly three decades later, research interests have again peaked in the area of ultrathin membrane optics.

Although space is a nasty environment for man-made satellites, it does offer some advantages. Bekey[39] proposed a concept for a revolutionary, ultralarge, ultralightweight satellite design. His idea is to use information webs instead of structural webs to control the static shape and pointing of a space-based membrane telescope. Bekey points out that "there is no need for any truss design in space—telescope trusses are a carryover of earth-bound thinking."[39] Bekey's telescope idea uses a precision-controlled figure sensor, a precision-controlled scanning electron beam, and a membrane mirror. His proposed mirror consists of a shape-memory alloy film to gain initial static shape, a piezoelectric film for finer, adaptive membrane control, and a liquid crystal stage to correct any residual errors. Bekey calls for a technology enabling road map to be developed to see such a membrane developed. Precision flying of satellites and aeronautical structures in general continues to be an active area of research.

Membrane mirrors meeting Bekey's proposed integrated characteristics have not come to fruition, but steps are being made in that direction. In a similar fashion, Main et al.[40] proposed a noncontact methodology for controlling the static shape of thin film mirrors. The authors used a feedback control system with an electron gun to manipulate the surface of a PVDF bimorph mirror. Through a series of experiments, Main et al.[40] demonstrated that an electron gun could be used to discretely control the surface of an active mirror. The drawback of such a concept, though, is the requirement of an additional structure to support and guide the additional hardware (such as an electron gun). As Bekey suggests, membrane mirrors and satellites need to peel away from ideas that demand additional structural supports and migrate toward concepts that integrate sensors and actuators within the structure itself.

Early[41] reports that the Lawrence Livermore National Laboratory has been developing techniques for fabricating meter size and larger Fresnel phase plate optics made of solar-sail materials. Other authors[42,43] have proposed the concept of using amplitude zone plate optics as part of solar-sail systems, but the Lawrence Livermore Laboratory proposes using corrective optics to broaden the limited frequency bandwidth of previous designs. Early's design uses a transmissive primary optic in the telescope design and illustrates the Lawrence Livermore Laboratory's capabilities for the design and manufacturing of amplitude zone plates made of sail materials.[41]

Dixit et al.,[44] also from the Lawrence Livermore Laboratory, experimentally tested a "50 cm diameter, f/100, 4-level diffractive lens in a fused silica substrate."[44] The lens is part of a much larger project known as Eyeglass, with the goal of meeting the stringent surface requirements and optical resolution of a future gossamer space telescope. Eyeglass tackles the issue of folding and unfolding an ultralarge mirror, from how to design for such anticipated motions to how to manufacture optical-level quality components that can perform such motions. As material science progresses and provides engineers with optical quality polymeric materials for ultralarge space mirrors, the results of Dixit et al.'s experimental work[44] will be directly applicable to other lens designs.

From these many research projects, certain key technological obstacles continue to rear their ugly heads. One of these main causes for concern is wrinkles in primary membrane mirrors or communication arrays. This topic will be addressed in the next section.

Technology Hurdle: Wrinkle Prediction and Analysis

Wrinkles continue to bother younger and older researchers alike in the field of membrane mirrors and deployable satellites. Membrane materials inherently cannot sustain a compressive stress field and react accordingly by creating out-of-plane displacements—wrinkles. Much work has already been done in the field of membrane mechanics. Jenkins[45] provides an excellent literature survey on the mechanics of membrane structures. His review covers over 120 references in the field of membrane mechanics on topics such as membrane response analysis, axisymmetric and nonaxisymmetric problems, vibration and dynamic response of membranes, wrinkling, underconstrained pneumatic envelopes, and experimental methods for analyzing the nonlinear behavior of membranes. Solar sails, a particular example of gossamer technology that is severely taxed by the formation of structural wrinkles, are summarized in a paper by Garner and Leipold.[46]

In 1998, Greschik et al.[47] presented research on the obtainable accuracy of an inflated membrane reflector. Their study investigated the impact of representative solution approximations on the accuracy of analytical shape predictions. The authors focused in particular on performing a parametric study of axisymmetric, linear elastic isotropic membranes using a newly developed software tool called Axisymmetric Membrane. The software tool, written in C, contains a numeric shape solver, a symbolic solver, an inverse solver, and evaluation modules like a shape comparator and a shape optimizer. Some general results from the authors' parametric study included observing that at higher pressures, greater errors occur in the expected shape of the membrane; of the considered geometric linearizations, small-angle approximations affect the greatest errors; and ignoring the radial component of Hencky's solution substantially degrades the accuracy of the model. The Greschik et al.[47] study also looked at the effect that wrinkling has on the expected shape of the membrane dish. The authors found that ignoring the wrinkling phenomenon caused either by temperature disturbances across the membrane or from perturbations to the membrane's edge led to erroneous results (especially in shallow membrane dish designs). Therefore, the authors conclude that modeling wrinkling in membrane dish designs is critical for shape prediction accuracy.

In 1999, Accorsi et al.[48] looked at the issues of damping and wrinkling in the modeling of parachutes. To address the issue of structural damping, the authors developed two new massless elements for their finite element model called "kink" and "fold" elements to simulate local damping in a parachute structure. Their finite element results provided a stable solution when modeling the deployment of the parachute canopy. The authors also address the importance of modeling wrinkles in their finite element work. They used a geometrically nonlinear finite element method in conjunction with a total Lagrangian formulation and convected curvilinear coordinate system.[48] In principle, the approach is to describe "the wrinkled state variables in the principle system, then transform this state to the convected system to perform the calculations."[48] Again, as with Greschik et al.,[47] the authors found that including the wrinkling theory in their analysis was critical to developing a stable, proper deployment model. Blandinao et al.[49] addressed mechanical and thermal loadings of a thin film membrane experimentally.

Murphey[50] investigated the effect of wrinkles on the in-plane stiffness characteristics of thin films. The author specifies the nomenclature for describing wrinkles. First, material wrinkles are "permanent out-of-plane deformations resulting from imperfections in manufacturing processing or from yielding of the material when it is folded in a tight radius."[50] Second, the author distinguishes material wrinkles from structural wrinkles, which are caused by "buckling of thin films under compressive stresses."[50] Further, wrinkles can be classified as either random or systemic. Random wrinkles result from "uniformly crushing a thin film to varying degrees"[50] and are assumed to be homogeneous and directionally independent at scales much larger than a single wrinkle. Systemic wrinkles are generated by "folding or otherwise creasing a thin film in a specific, repeating pattern."[50] Unlike random wrinkles, systemic wrinkles typically demonstrate directional dependence. The authors performed analytical analyses on 1.0-mil clear Kapton membrane undergoing a biaxial loading. They then validated their analytical results experimentally. The main finding by the authors is that wrinkles cause an "extremely non-linear behavior in thin films at low stress levels," and that "material bending as opposed to stretching is the dominant deformation mechanism."[50] Further, the author noted that the material bending mechanism, in conjunction with wrinkle and bubble kinematics, is responsible for a negative Poisson's ratio observed in their experiments. This effect should be noted in developing suitable models for membranes with wrinkles. Murphey and Mikulas[51] develop a continuum constitutive model for the elastic effects of material wrinkles in thin films. The benefit of Murphey's model is that it can be incorporated as a hyperelastic material in most commercially available finite element codes, thus enabling the software to deal with arbitrary material wrinkles.

Adler and Mikulas[52] developed a process called the iterative membrane properties (IMP) method to incorporate the effects of wrinkles on membrane elements in finite element models. The IMP method iteratively takes into account the formation, extent, and shape of wrinkles within a region of a structure, and then modifies the element material properties accordingly. The advantage of the IMP method is that it allows an engineer to develop a finite element model of an intended membrane structure design, see the effective wrinkled regions, and then modify the design to eliminate or reduce the wrinkled region. Adler and Mikulas[52] successfully validated their procedure on a wrinkled scale model of the James Webber Space Telescope solar shield.

Yang et al.[53] proposed a wrinkle modeling technique substantially different than Murphey.[50] Instead of an iterative process, the authors developed a method called the bar-networking approach, or BNA, that models a membrane as a network of bars with a special, nonlinear constitutive relation governing the dynamics. The BNA is based on the use of a parametric variational principle and a mathematical programming procedure. The BNA predicts wrinkled regions but does not address the frequency or amplitude of the developed wrinkles. The authors provide numerical simulations of their proposed wrinkle prediction methodology on a rectangular membrane, a square membrane, and an annulus membrane. Although such a method is able to predict wrinkle regions within a membrane, the holy grail of membrane wrinkle research is a model that can predict three key characteristics: 1) the wrinkled region, 2) the spatial wrinkle frequency, and 3) the wrinkles' amplitudes. These three goals should be kept in mind by researchers in this field.

Reynolds et al.[54] studied the vertical height of wrinkles in thin, stretched membranes as a function of time. The authors used a Bausch and Lomb optical micrometer (resolution 5 μ) to measure the surface height of wrinkles in a square Kapton membrane subject to an evenly distributed biaxial loading. The study focused on smaller, localized wrinkles as opposed to larger, global wrinkles in the sample. Wrinkle magnitudes were measured in predetermined locations at 15, 45, and 75 min and 24 h after the initial mounting. The authors found that under constant load, "the average height of the surface profile tended to decrease with time regardless of the stresses applied."[54] The authors noted a nonlinear behavior in the relaxation of the wrinkles, but also pointed out that their study suggests that tensile loading alone is not sufficient for eliminating or even nearly eliminating static wrinkles. Even though tensile loading alone might not eliminate wrinkles from a membrane structure, the development and integration of near-net shape membranes with active boundaries and active surface actuation will lead to successful gossamer systems.

Lopez et al.[55] have also looked at the formation of wrinkles but in unidirectionally tensioned membrane samples. The authors used a nonlinear finite element package in ANSYS to predict the formation of wrinkles when a shear load was applied to one side of a membrane strip. The results of their analysis showed decent agreement between the location of wrinkles and their amplitudes. However, a more important observation from this work was the importance of properly modeling the boundary conditions of the test structure. Improper modeling of even the simplest of boundary conditions can lead to erroneous results.

Along those lines, Holland et al.[56] looked at how the dynamics of a 2-m solar sail were influenced by the axial loads imposed by structural boundary booms. The authors clearly state that the purpose of their research is not to validate an upcoming flight mission, but rather to design a controlled experiment that can be used as a baseline for developing proper finite element modeling techniques for predicting the dynamic behavior of membrane structures under axial loading. Such baseline tests and documented research tracks are critical to continued technological developments in the modeling and prediction of gossamer structure dynamics.

Blandinao et al.[57] investigated the behavior of wrinkles under thermal and mechanical loads. The authors subjected a square Kapton membrane (0.013 mm thick) to mechanical loads through discrete points in the membrane's corners via Kevlar threads. The sample was also subjected to a thermal load by a radiant heater positioned 25.4 mm from the membrane. Mechanical analysis of the formed wrinkles was performed using a capacitance-type proximity sensor as well as photogrammetry techniques. Thermal measurements were taken of a separate but identical membrane using thermal imaging techniques to understand the temperature distribution throughout the membrane. Under an isothermal loading, the test data showed an increase in the number (or frequency) of wrinkles, a decrease in the magnitude of the wrinkles, but negligible change in the affected wrinkle region of the sample. Interestingly enough, the authors also noted from their thermal experiments that the hottest regions on the membrane actually occurred at the wrinkled corners of their sample, furthest away from the applied heat source. The authors speculate that the cause of this phenomenon is linked to the increased surface area in the wrinkled regions, thus harvesting the greatest heat. In any case, the authors comment that wrinkling must be considered in the future thermal analysis of membrane structures. Again, the authors' conclusions further enhance the necessity of a multidisciplinary approach that must be taken when working with gossamer structures.

Blandinao et al.[58] performed a similar mechanical and thermal loading experiment on a square Kapton membrane. Building upon the work of Blandinao et al.,[57] the authors actually measured the amplitude of the consequent wrinkles formed by isothermal asymmetric mechanical loading as well as combined symmetric mechanical and asymmetric thermal loadings. Contour plots were created from the top-left corner of the membrane sample. The authors observed that their testing techniques are effective for analyzing large-scale, large-wavelength wrinkle regions. Fair agreement was found between the experimental results from the experiments and the results from an ABAQUS finite element model of the membrane sample (Fig. 7). ABAQUS was able to account for the material wrinkles because of a user-defined subroutine called UMAT.[59]

Ding et al.[60] proposed a two-variable parameter membrane model for the prediction of wrinkles. Similar to Yang et al.,[53] Ding et al. based their formulation on the parameter variational principle and thus eliminated the need for an iterative solution. Their defined model introduces two viable parameters into the constitutive matrix to identify a membrane region as taut, slack, or wrinkled. The authors then present a numerically efficient nonlinear mathematical algorithm that solves (without iteration) the regions of taut, slack, and wrinkled states. Three numerical simulations are presented and verified, corresponding to a rectangular sample, a square sample, and an annulus sample. Unlike Yang et al.,[53] Ding et al. performed a preliminary experiment with a square Kapton membrane sample to verify their predicted results. Good agreement was found between the model and experiment.

Lee and Lee[61] developed a finite element procedure using assumed strain formulation solid shell elements to handle ultrathin materials. The authors outline a methodology to introduce a modified modulus into the solid shell elements. By doing so, the effectiveness of the element is increased three orders of magnitude with regards to the length/thickness ratio of the element (from 10^5 to 10^8). The authors also suggest that their element, combined with a fictitious damping, is able to model wrinkle formation. However, to induce numerically out-of-plane displacements, the authors added a small geometric imperfection in the form of a trigonometric function. This method is more in line with a geometrically nonlinear analysis. Although this work and related research has shown promise, research into the use of the finite element method while preserving the physics of the system should be emphasized and pursued.

Johnston[62] used an ABAQUS finite element model to model the dynamic development of wrinkles in the James Webber Space Telescope sunshield. The methodology used for the finite element model was the same methodology presented by Blandinao et al.[58] but originally developed by Adler.[59] Johnston used the model to analyze the dynamic behavior of the sunshield, including identifying key structural modes. Johnston then carried out a parametric study to investigate the effects of varying the preload applied to the sunshield model. He observed that the membrane stresses were predicted to increase linearly and that the size and shape of the wrinkles would not change much. Johnston then performed an actual modal analysis test on a 1/10th-scale sunshield. For the dominant sunshield modes, his predicted modal frequencies were within 15% of the measured frequencies, with most frequencies aligning within 8% difference.

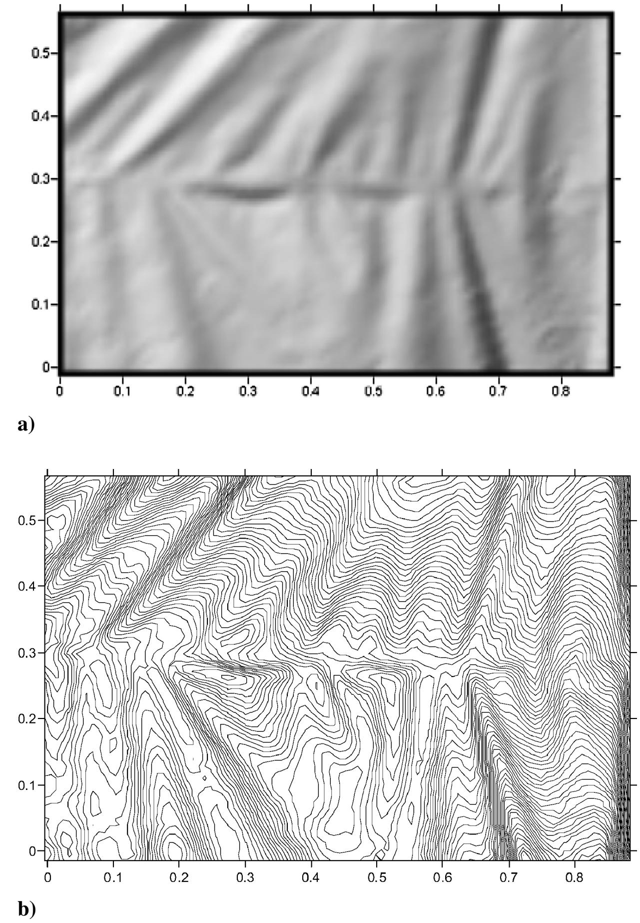


Fig. 7 Wrinkled membrane sample: a) contour plots and b) topographical maps. Figures courtesy of NASA/R. Pappa.

Wong and Pellegrino[63] researched a methodology for predicting the out-of-plane amplitude and wavelength of wrinkles developed in a square solar-sail sample. The solar sail has loads applied at 45-deg angles at each corner (in the direction of the square sample's diagonals). The authors discuss the development of an analytical model that assigns different stress fields to different portions of the square membrane. Building on the work of Wong et al.,[64] the authors are able to predict the formation, amplitude, and wavelength of wrinkles developed under different loading conditions at the corners of the membrane. They based their comparisons on a developed ABAQUS finite element model, as well as an experimental setup consisting of a Kapton membrane. In general, the ABAQUS model and the experimental results were in good agreement with each other, both in terms of wrinkle amplitudes as well as wrinkle wavelength. This work is truly a landmark in the gossamer community, as it thus far is one of the only research endeavors that captures the three key areas of interest with wrinkles, namely, 1) the wrinkled region, 2) the spatial wrinkle frequency, and 3) the wrinkles' amplitudes.

Leifer et al.[65] investigated the possibility of using SRS Technology's proposed solution to wrinkle elimination. SRS Technology suggests the use of a shear compliant border to prevent shear effects from the border or supporting structure from entering into the usable region of the membrane. The authors built finite element models in ANSYS, with each model using more than 6000 SHELL63 elements. One model looked at a square membrane sample under shear loading, and the others included 19.05-, 25.40-, 31.75-, and 38.10-mm shear compliant borders, respectively. Each model was 0.2386 m^2 and made from 0.0762-mm-thick Mylar. An experimental setup enforced a shear loading condition on a square Mylar sample of equal dimension as the finite element model. Wrinkle measurements were taken using photogrammetric testing techniques. The authors observed good correlation between their experimental results and their predicted results from their ANSYS finite element analysis. An extension of this research that needs to be pursued is dynamic testing of shear-compliant border structures to understand their behavior under dynamic loading.

Su et al.[66] investigated the time evolution of wrinkle development in a square membrane structure using buckling and postbuckling solutions in a software code called GENOA. Their particular code was incorporated with an updated Lagrangian method[67] to account for the nonlinear behavior of the membrane under a time-varying load. The authors compared their results and noticed similar trends in an experimental setup. For example, as the load was increased on the membrane sample, the amplitude of the membrane wrinkles tended to decrease. However, after the load reached a critical value new wrinkles would start to form in the central edge areas of the membrane. These new wrinkles formed from the existing, precritical load wrinkles.

Tessler et al.[68] studied a geometrically nonlinear, updated Lagrangian shell formulation to simulate the formation of wrinkles in thin-film membranes using ABAQUS. The authors modeled a square membrane using S4R5 shear-deformable shell elements. One of the biggest challenges the researchers had to overcome was the issue of deformation coupling between bending and membrane deformation. To get around this issue, the authors applied pseudorandom out-of-plane imperfections to the (initially) planar membrane surface, thus invoking the membrane-to-bending coupling, and consequently convergent wrinkled equilibrium states were obtained. (This methodology is similar to that imposed by Lee and Lee.[61]) Further, the pseudorandom imperfections artificially placed in the model were demonstrated to be independent of the final, convergent solution. The authors concluded from their work that the current state-of-the-art computational methods have the potential for adequately simulating the structural response of highly flexible, ultrathin structures.

Kukathasan and Pellegrino[69] analyzed the nonlinear vibration of wrinkled membranes. In a systematic approach, the authors looked at using a finite element (FE) model (ABAQUS and the iterative membrane properties user subroutine) to predict the first six to nine mode shapes, damped natural frequencies, and damping ratios of a square Kapton membrane. The authors performed a static and dynamic analysis on a membrane model both with wrinkles and without wrinkles and both in air and in vacuum. The FE model of the wrinkled membrane vibrating in air accurately predicted the mode shapes and frequencies when compared to existing experimental data. Data were unavailable for in vacuum responses of the membrane. The authors demonstrated that a linear-elastic model of a membrane (without wrinkles) can be used to accurately predict the modal response of a moderately wrinkled membrane but not that of a heavily wrinkled membrane. In fact, the authors comment that the results apply both in air and in vacuum, as well. Second, the authors also looked at using linear and non-linear system identification techniques with the square membrane. Under certain tensile loads, the membrane was subjected to a broad-band sine sweep excitation (from 0 to 50 Hz) applied by an electromagnetic shaker, and the response of the membrane was measured by a Polytec PSV300 scanning laser vibrometer. The linear analysis was used to identify the first few modes and associated damping ratios of the membrane in air. The authors then focused in on the first three modes of the membrane and created a sonogram of the experimentally measured response against time and frequencies. A sonogram is "a collection of Fourier transforms for successive time windows [that] maps out the response of the membrane at continuously varying excitation frequencies."[69] The results of the sonogram demonstrated that the damping increases in the first three modes of the membrane as the excitation frequency is increased. Further analysis by the authors indicated that the response of the membrane is characterized by a hardening nonlinearity and demonstrated the presence of quadratic and cubic nonlinearities.

Another area of research concerning the gossamer structure modeling community is developing models that capture the effect of gravity-induced loading on gossamer structures. Gravity-induced loading can cause structural wrinkles during ground testing that might not be present in a space-deployed structures. Johnston et al.[70] attack the issue of gravity-induced sag through a nonlinear finite element analysis. The authors were able to predict the peak deflection of two solar-sail samples under gravity-induced loading to within 10% of their measured values.

Smith et al.[71] also conducted experimental research to study the effect of gravity on gossamer structures. However, as opposed to the solar sails investigated by Johnston et al.,[70] Smith et al. looked at the effect gravity had on the deployment of inflatable tubes. The authors found that deployment of the tubes in a 1-g environment consistently demonstrated a "pressurization delay" during the unfolding process that was not present during their 0-g tests. Follow-up work was pursued by Black et al.[72] in 2004 further correlating experimental and analytical results that include the effect of gravity-induced sag. Related experimental and analytical work with inflated tubes can be found in Smith and Main,[73] Clem et al.,[74–76] Welch and Smith,[77] Hobbs et al.,[78] and Campbell et al.[79]

Meyer et al.[80] performed 1-g and 0-g experiments on a 1-m-scale model parabolic reflector using photogrammetry techniques. They found that in 0-g conditions surface ripples were less pronounced compared to the 1-g case despite having identical boundary conditions. Distinguishing the response of gossamer structures in and out of a significant gravitational field is critical to the technological roadmap for getting gossamer structures in space.

The combination of analytical and experimental work in the area of wrinkle prediction and identification has led to significant advancements in our ability to model gossamer membrane structures. Analytical tools continue to be developed to aid in the system-level design of membrane structures. Future research efforts need to continue to develop these analytical tools so that wrinkles are a well-understood (and hence, well-predicted and thereby controlled) phenomenon. Further, researchers should focus their attention on modeling techniques that preserve the true physics of the system. As models continue to mature, effective control methodologies will concurrently develop, as well. The next section will address advancements in the area of gossamer spacecraft and membrane optic control systems.

Recent Trends in Gossamer Control Systems

Controlling Gossamer Space Structures

Coinciding with wrinkle research has been the development of control methodologies to effectively control both the dynamics of ultraflexible structures and the prevention/elimination of wrinkles from large, ultrathin lenses. In 1982, Bales et al.[81] provided a detailed mathematical framework of possible controllers and their incorporation with large space structures. Bales et al.[81] discuss reduced-order models, reduced-order controllers, partial differential equation control and stabilization techniques, adaptive control techniques, and many other control-related topics. Their survey work does not address wrinkling in particular, but many of the trends identified by his research apply to the current state of the art in large space structure control.

Fast forward to 2001, as Salama and Jenkins[82] review recent developments and trends in gossamer space structures. Salama and Jenkins[82] recognized that the future of ultralarge space structures lies in the development of embedded intelligent materials to both sense and control the dynamics of such systems. The authors refer to the new hybrid of intelligent materials in large apertures as precision gossamer apertures. Their survey includes methods for modeling membranes, actuator and sensor interactions (especially those made from piezoelectric, shape memory alloys, and other intelligent materials), and methods for monitoring the damage and health of large space structures on orbit.

In 2004, Ruggiero et al.[83] suggested that the gossamer control community shift their thinking from gossamer technology to SPIDER, or Super Precise Intelligent Deployables for Engineered Reconnaissance, technology. The name SPIDER also refers to earlier work by Jenkins[84] investigating the science of web building by arachnids here on Earth. By incorporating smart materials and actuators into the design of a membrane structure, system-level optical control might be possible. One of the key technologies identified in the paper is PolyMEMS (membrane-type polymers capable of electrostatic control). By incorporating PolyMEMS into the design of a large-scale membrane mirror, distributed actuation and sensing at the nanolevel could be achieved.

In line with Salama and Jenkins's[82] and Ruggiero et al.'s[83] work, several papers have been written addressing some of the key technological pathways to effectively controlling ultralarge space structures. Quadrelli and Sirlin[85] derive the equations of motion describing the behavior of the membrane of a gossamer spacecraft, which can then be used in designing control algorithms. Thinking in line with an active, integrated control system for a gossamer spacecraft, Williams et al.[86] looked at the local effects caused by bonding active piezopolymer (PVDF) to the skin of an inflated gossamer structure. The authors demonstrated that membrane-based modeling of gossamer structures with attached intelligent materials leads to erroneous results. The authors suggest that thin plate theory is the preferred method of modeling, as it allows the system model to capture both the added mass and added stiffness of the attached active film, two characteristics that are critical in the proper modeling of a dynamic model.

Baruh[87] investigated the use of segmented piezoelectric sensors and actuators to control both the rigid-body dynamics as well as the elastic motions of a flexible structure. Baruh derives the equations of motion and control laws for controlling a double-link structure with elasticity. An important result of this work is that the control laws designed for the elastic motions of a structure can be tailored independently of the rigid-body control. In a similar fashion, Miyazaki-Kawasaki and Furuya[88] numerically demonstrated static shape control on a folded membrane with piezoelectric film patches bonded along the creases of the folded membrane. The authors performed numerical simulations of deploying the accordion-like membrane and measured the overall surface distortion after actuating the piezoelectric seam actuators. Using thin piezofilms, the authors demonstrated that reasonable surface accuracy could be obtained of the membrane using small input voltages. Further, Jenkins and Schur[89] looked at designing deployable antennas purposefully assembled with seams in the same way that a bat's wing is formed. The bat analogy would allow for deployment and surface shape precision if properly incorporated within the seams of a large-scale antenna. An ABAQUS simulation of an active gore/seam model was conducted, and it was shown that by heating the seams in the model (thus causing them to expand) almost all of the structural undulations from the surface are removed. Further work in this area was conducted by Duvvuru et al.[90] Such technology can prove fruitful in the area of deployable radar or antenna technology, but would most likely be detrimental to the nanometer surface accuracy necessary for a spaceborne optic.

Gorinevsky et al.[91] proposed the use of distributed, localized shape control for gossamer structures. The authors define a large space aperture consisting of thousands of identical cells. Each cell contains a control actuator, sensor, and computational element to provide local control of the aperture surface. The unique feature of the authors' proposed control methodology is that each aperture cell would make a surface correction based on a time history of sensor signals as well as the status of those cells in the primary cell's immediate neighborhood. Although the control algorithms necessary for such a distributed system are possible to develop, the authors identify that the actuator, sensor, and computational technology necessary for implementing such a smart cell is currently in its infancy. However, this type of analysis and proposed control technology is an important contribution toward the future of control and system modeling.

Tzou et al.[92] also address the issue of distributed control design, although they focus on developing the structural dynamics of conical shells laminated with piezoelectric actuators. Further, Tzou et al.[93] applied their distributed control results to understand the local effects laminated piezoelectric patches would have on the surface of a toroidal shell. Their work outlines the necessary structural dynamics and sensor/actuator interactions for accurate microlevel control of a toroidal skin and is fundamental to the future of integrated smart structures and gossamer spacecraft.

Peng et al.[94] used a genetic algorithm and neural network to perform active control of inflatable structure membrane wrinkles. Control is performed via actuators at the four corners of a square membrane sample. The genetic algorithm is used to find the optimal control levels in each of the four actuators that produce the smallest spatial frequency and amplitude of resultant structural wrinkles in the sample. Further, the concept demonstrates numerically that it can estimate the flatness of the membrane.

Jha and Inman[95] designed a sliding mode controller to control unwanted dynamics of an inflated torus. The inflated torus is a possible boundary constraint for ultralarge lenses, and controlling the dynamics of the boundary will help mitigate unwanted dynamics from affecting the lens. The numerical simulations provided by the researchers use segmented PVDF patches as sensors and actuators around the perimeter of the torus. Sliding mode control is suggested as a good control scheme because it is able to take into account the presence of unknown system dynamics. The closed-loop response of the implemented system reduced the settling time of the simulated torus by 75%. Similarly, Sung[96] designed an estimator-based sliding mode controller to help maneuver a flexible spacecraft. The research demonstrated through numerical simulation that the designed controller could handle the space shuttle performing a 30-deg roll maneuver and maintain line-of-sight tracking with an extended antenna.

Glaese and Balas[97] researched the area of dynamic tailoring with regards to ultraflexible gossamer structures. The test structure consisted of an inflated torus at the boundary and a membrane mirror held within the interior of the torus by discrete springs. Three reaction masses were added to the torus to simulate three attachment points from a supporting secondary mirror structure. Dynamic disturbances were introduced to the mirror through the three reaction masses. Piezoelectric polymer patches were attached to the torus at these three critical junctions and setup in a shunting circuit. The shunting circuit was able to reduce broadband vibration levels experienced by the membrane, while passive tuned-mass-dampers were able to attenuate narrowband disturbances. The overall demonstration of vibration attenuation and control by the research team provides a strong example that vibration identification and control with ultralight, ultraflexible gossamer structures through the use of integrated smart material systems is indeed a viable option.

Solter et al.[98] investigated a possible methodology for membrane boundary control. The research focuses primarily on the design and implementation of a newly developed actuator capable of applying in-plane tension and out-of-plane excitation to a membrane mirror, lens, or communications aperture. The actuator, designed and fabricated at NASA Langley Research Center, replaced one of the membrane support cables in the prototype hexapod structure (the same structure analyzed by Adetona et al.[20]). Testing of the actuator demonstrated limited in-plane tension adjustment capabilities but fair capacity to provide out-of-plane excitation for the structure. A preliminary control experiment with a lead-lag controller showed that the actuator was able to reject dynamic disturbances beyond 15 Hz.

Controlling Ultralightweight Space Optics

Some researchers of late have focused their efforts on trying to actively control the mirror or aperture of an ultraflexible spacecraft. Rogers and Agnes[99] used a finite element approach based on the method of integral multiple scales to analyze an axisymmetric, piezothermoelastic laminated plate model representing an active optic element. The results of the research presented show that a piezoelectric polymer adhered to the nonreflective surface of an inflatable optical reflector can have a significant effect on the wavefront being measured. Further, the laminate also could be used as an active vibration suppression element. Sobers et al.[100] followed up the work performed by Rogers and Agnes[99] by constructing two optical mirrors with differing PVDF active material etchings. The first mirror was constructed with two concentric circular etchings, and the second mirror was constructed with six triangular etchings surrounding a circular, central etching. Tests were conducted to see the influence the PVDF surfaces could enforce onto a General Electric Silicones RTV615 reflective surface. Surface measurements were taken using a Shack–Hartmann wavefront sensor. Mirror 1 demonstrated that global curvature of a lightweight membrane mirror could be obtained using a piezopolymer control layer. Mirror 2, with its complicated etching pattern, demonstrated that higher-order wavefront aberrations could be accounted for and eliminated. Both tests confirmed that active membrane elements are a viable option for future membrane mirror designs. However, there is still a concern as to the manufacturability of a "smart lens," especially at large scales, to the optical (nanometer) tolerances necessary for reconnaissance mission requirements.

Flint and Denoyer[101] used MSC NASTRAN to research the ability of internal, segmented patch actuators to counteract surface wavefront aberrations. However, unlike other researchers, the authors propose a top-down approach to achieving desired surface accuracies. Instead of studying the current limits of actuator technology for achieving global control of a membrane, the authors suggest starting with particular surface requirements and prescribing the control stroke of the necessary actuator. After developing a method to drastically reduce the order of the membrane model under aberration, the authors demonstrate that they can efficiently and optimally place segmented actuators to account for the surface aberration. The authors' innovative approach can prove quite useful, as the prescribed requirements for sensors and actuators can spur technological advancements in this area.

Hoagg et al.[102] designed an adaptive controller to eliminate dynamic disturbances to a drum head using a matrix of speakers behind the plane of the drum membrane. The test setup used acoustic excitation (from a disturbance speaker) and an optical sensor to measure the response of the drumhead. The authors were able to reduce the vibration levels of a single-tone disturbance of 115 Hz by 40 dB. Although such a control system would require a separate structure to house the actuation speakers, the idea demonstrates superiority over ideas such as electrostatic actuation (a nonlinear actuator) or an electron gun (which requires significant secondary structures and precision components).

Gullapalli et al.[103] provide research on the use of nanolaminate technology to construct near-net shape, optical quality, and ultralightweight mirrors. Such research is being performed at the Lawrence Livermore National Laboratories. The fabricated nanolaminate mirrors have significant in-plane stiffness, a superior quality when compared to traditional membrane materials. However, Gullapalli et al.[103] suggest the use of a newly designed inchworm actuator (250-μ stroke, resolution of a few nanometers, weighing only 10 mg) combined with a distributed, flexure-hinged truss substrate to provide the surface wavefront control necessary for optical applications. A benefit of the proposed nanolaminate and truss substrate combination structure is that it highly tolerant for large coefficient of thermal expansion mismatches as well as severe temperature gradients along the mirror's face. Further advances in wavefront control with active mirrors can be found in Redding et al.[104]

Witherspoon and Tung[105] investigated a microelectromechanical-systems-based flexible sensor and actuator system for static shape control and structural health monitoring of a gossamer structure. The authors' research looked at using electroactive-polymer (EAP) materials for controllable surface manipulation of a lens or aperture. However, as the authors point out, EAP materials must (at least currently) be operated in a hydrated environment, and they have relatively weak actuation force. This combination of traits is not ideal for spaceworthy missions, and further research to improve EAP materials is essential.

The U.S. Air Force has shown considerable interest in the area of ultralarge, ultralight membrane optics. Recent efforts funded by the Air Force Research Laboratory have concentrated on the development of near-net shape membrane mirrors that can deploy to optical precision. Ash et al.[106] discuss their research of applying an optical coating to a membrane mirror to purposefully use the developed intrinsic stresses to create a desired lens shape. Gunderson et al.[107] followed up with Ash et al.'s [106] work by applying pressurization to an undercompensated, stress-coated parabolic membrane mirror to achieve zero apex displacement. The authors were able to model the use of pressure to correct the net shape of the optically coated membrane both analytically and using finite elements. Good agreement was found between the two methods. The idea of an optically coated membrane that produces a stress field during the curing process to curve the lens into a parabola is an exciting development in the field of membrane optics.

Heading into the 21st Century

Ultralight, ultraflexible space structures are a unique and fascinating research area. Their low mass, stemming from membranous fabrication techniques, poses difficult issues when modeling, designing, experimenting, and trying to control such structures. Belvin,[108] of NASA Langley Research Center, outlines some of the key challenges facing the design and implementation of large space structures and systems. NASA's goals for future radiometers, radars, and space optics specify some incredible characteristic numbers. For example, radiometers are expected to have 1.4–300-GHz operational frequencies from a 25–50-m array made of a mesh or membrane with an areal density less than 2 kg/m^2. Space optics for the visible range of light are expected to be 6–10 m in diameter and have an areal density of less than 5 kg/m^2.

At Defense Advanced Research Projects Agency (DARPA), a program has been created entitled the Innovative Space-Based Antenna Technology program to develop large, deployable radar antennas. Also coming out of the Special Projects Office at DARPA is the Integrated Sensor Is Structure program, which is developing an ultralarge, ultralightweight phased-radar antenna to sense incoming cruise missiles at 600 km and deployed ground troop movement at 300 km. An ultralarge aperture will be used to meet the radar requirements, instead of a high-powered dish. NASA's Jet Propulsion Laboratory is working with Lockheed Martin Space Systems to develop a Dual Anamorphic Reflecting Telescope[109] that will use two singly curved primary membrane mirrors to focus light onto a secondary mirror.

In response to NASA and DARPA's proposed outlines for the future of large spacecraft systems and optics, research efforts from multiple engineering and scientific disciplines are continually pushing back the boundary of knowledge. As part of the multidisciplinary approach to understanding the many facets of gossamer structures, new efforts are effectively integrating active smart materials into the design process of gossamer spacecraft. By blending active systems with gossamer structures, a new field of technology is taking shape that will help launch satellite capabilities to new levels. In the meantime, researchers must persevere in accurately modeling membranes, developing proven preflight validation techniques, and overcoming technological hurdles like membrane wrinkles. The 20th century was earmarked by the first controlled air flight by the Wright brothers, and with continued efforts the 21st century will be heralded by new spacecraft technology that exceeds our wildest dreams.

Appendix: Quick Access Reference Guide

Table A1 Quick access reference guide

Author	Year	Ref. no.	G.S. history	Mechanics of membranes	Membrane optics/ modeling	G.S. materials	Preflight validation	Modal analysis (traditional)	Modal analysis (smart mats)	G.S. satellite control reqs.	Mem. boundary control	Wrinkle modeling	Wrinkle experiments	Finite element models	Photogram-metry	JWST sunshield	Surface accuracy	Amp. zone plates/ optic mat.	Smart mat. models	Static/ dynamic control	Techno-logical challenges
Accorsi et al.	1999	48	—	X	—	—	—	—	—	—	—	X	—	X	—	—	—	—	—	—	—
Adetona et al.	2003	20	—	—	X	X	X	X	—	—	—	—	—	X	—	—	—	—	—	—	—
Adler	2000	59	—	—	—	—	—	—	—	—	—	X	—	X	—	—	—	—	—	—	—
Adler and Mikulas	2001	52	—	X	X	—	—	—	—	—	—	X	X	—	—	X	—	—	—	—	—
Ash et al.	2004	106	—	X	X	—	—	—	—	—	—	—	—	—	—	—	X	—	—	—	X
Bales et al.	2003	81	X	—	—	—	—	—	—	X	—	—	—	—	—	—	—	—	—	X	X
Bales	1982	36	—	—	X	X	—	X	—	—	X	—	—	X	—	—	X	—	—	—	—
Baruh	2001	87	—	—	—	—	—	—	—	X	—	—	—	—	—	—	—	—	X	X	—
Bekey	1999	39	—	—	X	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	X
Belvin	2004	108	—	—	—	—	—	—	—	X	—	—	—	—	—	—	—	—	—	—	X
Blandinao et al.	2001	49	—	—	—	—	—	—	—	—	—	—	—	X	—	—	—	—	—	—	—
Black and Pappa	2004	28	—	—	—	—	—	—	—	—	—	—	—	—	X	—	X	—	—	—	X
Black et al.	2004	72	—	—	—	—	X	—	—	—	—	X	X	X	X	—	X	—	—	—	—
Blandinao et al.	2002	57	—	X	X	X	—	X	—	—	—	—	X	—	X	—	X	—	—	—	—
Blandinao et al.	2003	58	—	X	X	X	—	X	—	—	—	X	X	X	X	—	X	—	—	—	—
Blandinao et al.	2003	27	—	—	—	—	X	—	—	—	—	X	X	—	X	—	X	—	—	—	X
Cadogan et al.	2002	32	—	—	—	X	—	—	—	—	—	—	—	—	—	—	—	—	X	—	X
Cadogan et al.	1999	19	—	—	—	X	X	X	—	—	—	—	—	—	—	—	—	—	—	—	—
Campbell et al.	2004	79	—	—	—	—	X	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Cassapakis and Thomas	1995	1	X	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	X
Chesnokov and Vasileisky	1997	43	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	X	—	—	—
Choi et al.	2002	34	—	—	—	X	—	—	—	—	—	—	—	—	—	—	—	—	—	—	X
Clem et al.	2001	75	—	—	—	—	X	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Clem et al.	2000	74	—	—	—	—	X	—	—	—	—	—	—	X	—	—	—	—	—	—	—
Clem et al.	1999	76	—	—	—	—	X	—	—	—	—	—	—	X	—	—	—	—	—	—	—
Cook	1978	67	—	—	—	—	—	—	—	—	—	—	—	X	—	—	—	—	—	—	—
Darooka and Jensen	2001	31	—	—	—	X	—	—	—	—	—	—	—	X	—	—	—	—	—	—	—
Davis and Agnes	2002	6	—	—	—	—	X	—	—	—	—	—	—	—	—	—	—	—	—	X	X
deBlonk	2003	8	—	X	X	—	—	—	—	—	—	—	—	—	—	—	X	—	—	—	—
Ding et al.	2002	60	—	X	X	—	—	—	—	—	—	X	X	X	—	—	X	—	—	—	—
Dixit et al.	2002	44	—	—	X	X	—	—	—	—	—	—	—	—	—	—	X	X	—	—	—
Dorrington et al.	2003	29	—	—	—	—	X	—	—	—	—	X	X	—	X	—	X	—	—	—	—
Dragovan	2002	109	—	—	X	—	—	—	—	—	X	—	—	—	—	—	X	—	—	X	X
Duvvuru et al.	2003	90	—	—	—	—	—	—	—	—	—	—	—	X	—	—	X	—	X	X	—
Early	2002	41	—	X	X	X	—	—	—	—	—	—	—	—	—	—	X	X	—	—	—
Fang and Lou	1999	9	X	—	X	—	—	—	—	—	—	—	—	X	—	X	—	—	—	—	—
Flint and Denoyer	2003	101	—	X	X	—	—	—	—	X	—	—	—	X	—	—	X	—	X	X	—
Flint and Glaese	2001	33	—	—	X	X	—	X	—	—	—	—	—	X	—	—	X	—	—	—	—
Flint et al.	2003	35	—	—	X	X	—	X	—	—	—	—	—	X	—	—	X	—	—	—	—
Forward	1984	42	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	X	—	—	—
Garner and Leipold	2003	46	X	—	—	—	X	—	—	—	—	—	X	—	X	—	—	—	—	X	X
Gaspar et al.	2004	17	—	—	—	—	X	—	X	—	—	—	—	X	—	—	—	—	—	—	—
Glaese and Balas	2004	97	—	—	—	—	—	—	—	—	X	—	—	—	—	—	X	—	X	X	X
Gorinevsky et al.	2001	91	—	—	X	—	—	—	—	X	—	—	—	—	—	—	X	—	X	X	X
Greschik et al.	1998	47	—	X	X	—	—	—	—	—	X	—	—	—	—	—	X	—	—	—	—
Grosso and Yellin	1977	37	—	—	X	X	—	X	—	—	—	—	—	—	—	—	X	—	—	X	—
Gullapallie et al.	2003	103	—	—	X	X	—	—	—	—	—	—	—	X	—	—	X	X	X	X	—
Gunderson et al.	2004	107	—	X	X	X	—	—	—	—	—	—	—	X	—	—	X	—	—	—	—
Hedgepeth	1981	5	—	—	—	—	—	—	—	X	—	—	—	—	—	—	—	—	—	X	X
Hoagg et al.	2003	102	—	—	X	—	—	—	—	X	—	—	—	—	—	—	X	—	—	X	—
Hobbs	1999	78	—	—	—	X	X	—	—	—	—	—	—	—	—	—	—	—	—	X	—
Holland et al.	2003	56	—	—	—	—	X	—	—	—	—	X	X	X	—	—	—	—	—	—	—
Jenkins	2001	45	—	X	X	—	—	—	—	—	—	X	—	X	—	—	X	—	—	—	X

(Continued)

Table A1 Quick access reference guide (continued)

Author	Year	Ref. no.	G.S. history	Mechanics of membranes	Membrane optics/ modeling	G.S. materials	Preflight validation	Modal analysis (traditional)	Modal analysis (smart mats)	G.S. satellite control reqs.	Mem. boundary control	Wrinkle modeling	Wrinkle experiments	Finite element models	Photogram-metry	JWST sunshield	Surface accuracy	Amp. zone plates/ optic mat.	Smart mat. models	Static/ dynamic control	Techno-logical challenges
Jenkins	2001	84	X	—	—	X	—	—	—	—	—	—	—	—	—	—	X	—	—	—	X
Jenkins and Schur	2001	89	—	X	—	—	—	—	—	—	—	X	—	—	—	—	X	—	X	X	—
Jenkins	1996	2	X	X	X	X	—	—	—	—	—	—	—	—	—	—	—	—	—	—	X
Jha and Inman	2004	95	—	—	—	—	—	—	—	X	X	—	—	—	—	—	—	—	X	X	—
Johnston	2002	62	—	X	—	—	—	X	—	—	—	X	X	X	—	X	X	—	—	—	—
Johnston et al.	2003	25	—	—	—	—	X	X	—	—	—	—	—	X	X	X	—	—	—	—	—
Johnston et al.	2004	70	—	—	—	—	X	X	—	—	—	—	—	X	X	—	X	—	—	—	—
Juang and Pappa	1985	21	—	—	—	—	—	X	—	—	—	—	—	—	—	—	—	—	—	—	—
Kukathasan and Pellegrino	2003	69	—	X	X	—	—	X	—	—	—	X	X	X	—	—	X	—	—	—	—
Lee and Lee	2002	61	—	X	X	—	—	—	—	—	—	X	—	X	—	—	X	—	—	—	—
Leifer et al.	2003	65	—	X	—	X	—	—	—	—	X	X	X	X	—	—	X	—	—	—	—
Lopez et al.	2004	55	—	X	—	—	—	—	—	—	X	X	X	X	—	—	—	—	—	—	—
Main et al.	1999	40	—	—	X	—	—	—	—	—	—	—	—	—	—	—	X	—	—	X	—
Marker and Jenkins	1997	7	—	X	X	—	—	—	—	—	X	—	—	—	—	—	X	—	—	—	—
Meyer et al.	2004	80	—	—	—	—	X	—	—	—	—	X	X	—	X	—	X	—	—	—	—
Miyazaki-Kawasaki and Furuya	2001	88	—	X	—	—	—	—	—	—	—	—	X	—	—	—	—	—	X	X	—
Murphey and Mikulas	1999	51	—	X	—	—	—	—	—	—	—	X	—	X	—	—	—	—	—	—	—
Murphey	2001	50	—	X	—	—	—	—	—	—	—	X	X	X	—	—	—	—	—	—	—
Pappa et al.	2001	23	—	—	—	—	X	X	—	—	—	—	—	—	X	—	—	—	—	—	X
Pappa et al.	2003	24	—	—	—	—	X	X	—	—	—	—	—	—	X	—	—	—	—	—	—
Pappa et al.	2003	26	—	—	—	—	X	—	—	—	—	—	X	—	X	X	—	—	—	—	—
Pappa et al.	2003	10	X	—	—	—	X	X	X	X	—	—	—	—	X	X	—	—	—	X	—
Peng et al.	2004	94	—	—	—	—	—	—	—	—	X	X	X	—	—	—	X	—	—	X	—
Quadrelli and Sirlin	2001	85	—	—	—	—	—	—	—	X	—	—	—	—	—	—	—	—	X	X	—
Redding et al.	2003	104	—	—	X	—	—	—	—	—	—	—	—	—	—	—	X	X	—	X	X
Reynolds et al.	2001	54	—	X	X	—	—	—	—	—	—	—	X	—	—	—	X	—	—	—	—
Rogers et al.	2002	99	—	X	X	—	—	—	—	X	—	—	—	X	—	—	X	—	X	X	—
Ruggiero et al.	2003	4	X	—	—	—	X	X	X	—	—	—	—	X	—	—	—	—	X	X	X
Ruggiero et al.	2003	14,15	—	—	—	—	X	—	X	—	—	—	—	—	—	—	—	—	—	—	—
Ruggiero et al.	2004	83	—	—	X	—	—	—	—	—	X	—	—	X	—	—	X	—	—	X	X
Ruggiero et al.	2004	13	—	—	—	—	X	—	X	—	—	—	—	—	—	—	—	—	—	X	—
Salama and Jenkins	2001	82	X	—	X	—	—	—	X	X	—	—	—	—	—	—	—	—	X	X	X
Slade and Tinker	1999	22	—	—	—	—	—	X	—	—	—	—	—	—	—	—	—	—	—	—	—
Smith and Main	2001	73	—	—	—	—	X	—	—	—	—	—	—	X	—	—	—	—	—	—	X
Smith et al.	2001	71	—	—	—	—	X	—	—	—	—	—	—	X	—	—	—	—	—	—	—
Sobers et al.	2003	100	—	X	X	—	X	—	X	X	—	—	—	—	—	—	X	—	X	X	—
Sodano et al.	2003	16	—	—	—	—	—	—	—	X	—	—	—	—	—	—	—	—	—	X	—
Solter et al.	2003	98	—	—	X	—	X	—	—	X	X	—	—	—	—	—	X	—	—	X	X
Su et al.	2003	66	—	X	—	—	—	—	—	—	—	X	X	X	—	—	—	—	—	—	—
Sung	2002	96	—	—	—	—	—	—	—	X	—	—	—	—	—	—	—	—	—	X	—
Takami and Iye	1994	38	—	—	X	—	—	X	—	—	—	—	—	—	—	—	X	—	—	—	—
Tessler et al.	2003	68	—	X	—	—	—	—	—	—	—	X	—	X	—	—	—	—	—	—	—
Tsunoda and Senbokuya	2001	30	—	—	—	X	—	—	—	—	—	—	X	—	—	—	X	—	—	—	—
Tzou et al.	2004	93	—	—	—	—	—	—	—	X	—	—	—	—	—	—	—	—	X	X	—
Tzou et al.	2002	92	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	X	X	—
Wada and Lou	2002	3	X	—	—	—	X	X	—	—	—	—	—	X	—	X	—	—	—	—	X
Welch and Smith	2003	77	—	—	—	—	X	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Whites and Knowles	2003	18	—	—	—	X	—	—	—	X	—	—	—	—	—	—	X	—	—	X	X
Wilkie et al.	2000	11	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	X	X	—
Williams et al.	2002	12	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	X	—	—
Williams et al.	2001	86	—	—	—	—	—	—	—	X	—	—	—	—	—	—	—	—	X	X	—
Witherspoon and Tung	2002	105	—	—	—	X	—	—	—	—	—	—	—	—	—	—	—	—	X	X	—
Wong et al.	2003	64	—	X	—	—	—	—	—	—	—	X	—	X	—	—	—	—	—	—	—
Wong and Pellegrino	2002	63	—	X	—	X	—	—	—	—	—	X	X	X	—	—	—	—	—	—	—
Yang et al.	2001	53	—	X	X	—	—	—	—	—	—	X	—	X	—	—	—	—	—	—	—

References

[1]Cassapakis, C., and Thomas, M., "Inflatable Structures Technology Development Overview," AIAA Paper 95-3738, April 1995.

[2]Jenkins, C. H., "Non-Linear Dynamic Response of Membranes: An Update," *Applied Mechanics Review*, Vol. 49, No. 10, Pt. 2, 1996, pp. S41–S48.

[3]Wada, B. K., and Lou, M., "Pre-Flight Validation of Gossamer Structures," AIAA Paper 2002-1373, April 2002.

[4]Ruggiero, E. J., Jha, A. K., Park, G., and Inman, D. J., "A Literature Review of Ultra-Light and Inflated Toroidal Satellite Components," *The Shock and Vibration Digest,* Vol. 35, No. 3, 2003, pp. 171–181.

[5]Hedgepeth, J. M., "Critical Requirements for the Design of Large Space Structures," NASA CR-3484, Nov. 1981.

[6]Davis, D. J., and Agnes, G. S., "Environmental Disturbance Modeling for Inflatable Space Structures," AIAA Paper 2002-1266, April 2002.

[7]Marker, D. K., and Jenkins, C. H., "Surface Precision of Optical Membranes with Curvature," *Optics Express*, Vol. 1, No. 11, 1997, pp. 324–331.

[8]deBlonk, B. J., "Selecting Models to Predict the Optical-Level Behavior of Membrane Primary Mirrors," AIAA Paper 2003-1653, April 2003.

[9]Fang, H., and Lou, M. C., "Analytical Characterization of Space Inflatable Structures—An Overview," AIAA Paper 99-1272, April 1999.

[10]Pappa, R. S., Black, J. T., Blandinao, J. R., Jones, T. W., Danehy, P. M., and Dorrington, A. A., "Dot-Projection Photogrammetry and Videogrammetry of Gossamer Space Structures," *Journal of Spacecraft and Rockets*, Vol. 40, No. 6, 2003, pp. 858–867.

[11]Wilkie, W. K., Bryant, R. G., High, J. W., Fox, R. L., Hellbaum, R. F., Jalink, A., Jr., Little, B. D., and Mirick, P. H., "Low-Cost Piezocomposite Actuator for Structural Control Applications," *Proceedings of the 7th SPIE International Symposium on Smart Structures and Materials*, Vol. 3991, Society of Photo-Optical Instrumentation Engineers (International Society for Optical Engineering), Bellingham, WA, 2000, pp. 323–334.

[12]Williams, R. B., Grimsley, B. W., Inman, D. J., and Wilkie, W. K., "Manufacturing and Mechanics-Based Characterization of Macro Fiber Composite Actuators," *Proceedings of the International Mechanical Engineering Conference and Exposition*, Aerospace Div., AD-Vol. 67, American Society of Mechanical Engineers, 2002, pp. 79–89.

[13]Ruggiero, E. J., Park, G., and Inman, D. J., "Multi-Input Multi-Output Vibration Testing of an Inflatable Torus," *Mechanical Systems and Signal Processing*, Vol. 18, No. 5, 2004, pp. 1187–1201.

[14]Ruggiero, E. J., Bonnema, G. T., and Inman, D. J., "Application of SISO and MIMO Modal Analysis Techniques on a Membrane Mirror Satellite," *Proceedings of 2003 ASME International Mechanical Engineering Congress and Exposition*, Aerospace Div., AD-Vol. 68, American Society of Mechanical Engineers, 2003, pp. 63–69.

[15]Ruggiero, E. J., and Inman, D. J., "A Comparison Between SISO and MIMO Modal Analysis Techniques on a Membrane Mirror Satellite," *Journal of Intelligent Material Systems and Structures*, Vol. 16, No. 3, 2005, pp. 273–282.

[16]Sodano, H. A., Park, G., and Inman, D. J., "An Investigation into the Performance of Macro-Fiber Composites for Sensing and Structural Vibration Applications," *Mechanical Systems and Signal Processing*, Vol. 18, No. 3, 2003, pp. 683–697.

[17]Gaspar, J. L., Mann, T., Behun, V., Wilkie, W. K., and Pappa, R. S., "Development of Modal Test Techniques for Validation of a Solar Sail Design," AIAA Paper 2004-1665, April 2004.

[18]Whites, K. W., and Knowles, T. R., "Electromagnetic Force and Torque Calculations for Fibrous Ultra-Lighweight Sails," *Electromagnetics*, Vol. 23, No. 8, 2003, pp. 681–696.

[19]Cadogan, D. P., Lin, J. K., and Grahne, M. S., "Development of Inflatable Space Radar Reflectarrays," AIAA Paper 99-1517, April 1999.

[20]Adetona, O., Horta, L. G., Taleghani, B. K., Blandinao, J. R., and Woods, K. J., "Vibration Studies of an Inflatable/Rigidizable Hexapod Structure with a Tensioned Membrane," AIAA Paper 2003-1737, April 2003.

[21]Juang, J.-N., and Pappa, R. S., "An Eigensystem Realization Algorithm for Modal Parameter Identification and Model Reduction," *Journal of Guidance, Control, and Dynamics*, Vol. 8, No. 5, 1985, pp. 620–627.

[22]Slade, K. N., and Tinker, M. L., "Analytical and Experimental Investigation of the Dynamics of Polyimide Inflatable Cylinders," AIAA Paper 99-1518, April 1999.

[23]Pappa, R. S., Lassiter, J. O., and Ross, B. P., "Structural Dynamics Experimental Activities in Ultralightweight and Inflatable Space Structures," *Journal of Spacecraft and Rockets*, Vol. 40, No. 1, 2003, pp. 15–23; also AIAA Paper 2001-1263, April 2001.

[24]Pappa, R. S., Black, J. T., and Blandinao, J. R., "Photogrammetric Measurement of Gossamer Spacecraft Membrane Wrinkling," *Proceedings of the 2003 SEM Annual Conference and Exposition on Experimental and Applied Mechanics*, Society of Experimental Mechanics, Bethel, CT, 2003.

[25]Johnston, J., Blandinao, J. R., Black, J. T., and Pappa, R. S., "Structural Analysis and Testing of a Subscale Sunshield Membrane Layer," AIAA Paper 2003-1742, April 2003.

[26]Pappa, R. S., Black, J. T., Blandinao, J. R., Jones, T. W., Danchy, P. M., and Dorrington, A. A., "Dot-Projection Photogrammetry and Videogrammetry of Gossamer Space Structures," *Journal of Spacecraft and Rockets*, Vol. 60, No. 6, 2003, pp. 858–867.

[27]Blandinao, J. R., Pappa, R. S., and Black J. T., "Modal Identification of Membrane Structures with Videogrammetry and Laser Vibrometry," AIAA Paper 2003-1745, April 2003.

[28]Black, J. T., and Pappa, R. S., "Photogrammetry and Videogrammetry Methods for Solar Sails and Other Gossamer Space Structures," AIAA Paper 2004-1662, April 2004.

[29]Dorrington, A. A., Jones, T. A., Danehy, P. M., and Pappa, R. S., "Laser-Induced Fluorescence Photogrammetry for Dynamic Characterization of Transparent and Aluminized Membrane Structures," AIAA Paper 2003-4798, July 2003.

[30]Tsunoda, H., and Senbokuya, Y., "Shape Measurement of a Flat Stretched Lightweight Membrane for Planar Antenna Structure," AIAA Paper 2001-1597, April 2001.

[31]Darooka, D. K., and Jensen, D. W., "Advanced Space Structure Concepts and Their Development," AIAA Paper 2001-1257, April 2001.

[32]Cadogan, D. P., Scarborough, S. E., Lin, J. K., and Sapna, G. H., III, "Shape Memory Composite Development for Use in Gossamer Space Inflatable Structures," AIAA Paper 2002-1372, April 2002.

[33]Flint, E. M., and Glaese, R. M., "Characterization, Prediction, and Improvement of Stretched Gossamer Membrane Dynamic Response," AIAA Paper 2001-1410, April 2001.

[34]Choi, S. H., Chu, S. H., Song, K. D., and King, G. C., "Microwave-Driven Multifunctional Capability of Membrane Structures," AIAA Paper 2002-5751, Sept. 2002.

[35]Flint, E. M., Bales, G., Glaese, R. M., and Bradford, R., "Experimentally Characterizing the Dynamics of 0.5m+ Diameter Doubly Curved Shells Made from Thin Films," AIAA Paper 2003-1831, April 2003.

[36]Bales, M. J., "Trends in Large Space Structure Control Theory: Fondest Hopes, Wildest Dreams," *Proceedings of IEEE Transactions on Automatic Control*, Vol. AC-27, No. 3, 1982, pp. 522–535.

[37]Grosso, R. P., and Yellin, M., "The Membrane Mirror as an Adaptive Optical Element," *Journal of the Optical Society of America*, Vol. 67, No. 3, 1977, pp. 399–406.

[38]Takami, H., and Iye, M., "Membrane Deformable Mirror for SUBARU Adaptive Optics," *Adaptive Optics in Astronomy*, Vol. 2201, 1994, pp. 762–767.

[39]Bekey, I., "A 25 m Diameter Space Telescope Weighing Less than 150 kg," AIAA Paper 99-4478, April 1999.

[40]Main, J. A., Martin, J., and Nelson, G., "Noncontact Shape Control of Membrane Mirrors," *Proceedings of the Ultra Lightweight Space Optics Challenge Workshop*, March 1999.

[41]Early, J. T., "Solar Sails—Fresnel Zone Plate Lens for a Large Space Based Telescope," AIAA Paper 2002-1705, April 2002.

[42]Forward, R. L., "Roundtrip Interstellar Travel Using Laser-Pushed Lightsails," *Journal of Spacecraft and Rockets*, Vol. 21, No. 2, 1984, pp. 187–195.

[43]Chesnokov, Y. M., and Vasileisky, A. S., "Space-Based Very High Resolution Telescope Based on Amplitude Zone Plate," *Proceedings of the International Conference on Space Optics*, Dec. 1997.

[44]Dixit, S., Hyde, R., Weisberg, A., Early, J., Rushford, M., and Britten, J., "Development of Large-Aperture, Light-Weight Fresnel Lenses for Gossamer Space Telescopes," AIAA Paper 2002-1203, April 2002.

[45]Jenkins, C. H. (ed.), *Gossamer Spacecraft: Membrane and Inflatable Structures Technology for Space Applications,* Vol. 191, Progress in Astronautics and Aeronautics, AIAA, Reston, VA, 2001.

[46]Garner, C., and Leipold, M., "Developments and Activities in Solar Sail Propulsion," AIAA Paper 2000-3858, July 2000.

[47]Greschik, G., Palisoc, A., Cassapakis, C., Veal, G., and Mikulas, M. M., "Approximating Paraboloids with Axisymmetric Pressurized Membranes," AIAA Paper 98-2102, April 1998.

[48]Accorsi, M., Lu, K., Leonard, J., Benney, R., and Stein, K., "Issues in Parachute Structural Modeling: Damping and Wrinkling," AIAA Paper 99-1729, April 1999.

[49]Blandinao, J. R., Johnston, J. D., Miles, J. J., and Soplop, J. S., "Thin Film Membrane Wrinkling Due to Mechanical and Thermal Loads," AIAA Paper 2001-1345, April 2001.

[50]Murphey, T. W., "The Constitutive Modeling of Thin Films with Random Material Wrinkles," AIAA Paper 2001-1347, April 2001.

[51]Murphey, T. W., and Mikulas, M. M., "Non-Linear Effects of Material Wrinkles on the Stiffness of Thin Polymer Films," AIAA Paper 99-1341, April 1999.

[52]Adler, A. L., and Mikulas, M. M., "Application of a Wrinkled Membrane Finite Element Approach to Advanced Membrane Structures," AIAA Paper 2001-4646, April 2001.

[53]Yang, B., Ding, H., Lou, M., and Fang, H., "A New Approach to Wrinkling Prediction for Space Membrane Structures," AIAA Paper 2001-1348, April 2001.

[54]Reynolds, R. R., Ferguson, T. P., and Funkhouser, J. C., "Measurement of Residual Wrinkles in Polymer Membranes," AIAA Paper 2001-1346, April 2001.

[55]Lopez, B. C., Lih, S.-S., Liefer, J., and Guzman, G., "Study of Ripple Formation in Unidirectionally-Tensioned Membranes," AIAA Paper 2004-1737, April 2004.

[56]Holland, D. B., Virgin, L. N., and Belvin, W. K., "Investigation of Structural Dynamics in a 2-m Square Solar Sail Model Including Axial Loading Effects," AIAA Paper 2003-1746, April 2003.

[57]Blandinao, J. R., Johnston, J. D., Miles, J. J., and Dharamsi, U. K., "The Effect of Asymmetric Mechanical and Thermal Loading on Membrane Wrinkling," AIAA Paper 2002-1371, April 2002.

[58]Blandinao, J. R., Pappa, R. S., and Black, J. T., "Modal Identification of Membrane Structures with Videogrammetry and Laser Vibrometry," AIAA Paper 2003-1745, April 2003.

[59]Adler, A. L., "Finite Element Approaches for Static and Dynamic Analysis of Partially Wrinkled Membrane Structures," Ph.D. Dissertation, Aerospance Engineering Dept., Univ. of Colorado, Boulder, CO, Dec. 2000.

[60]Ding, H., Yang, B., Lou, M., and Fang, H., "A Two-Variable Parameter Membrane Model for Wrinkling Analysis of Membrane Structures," AIAA Paper 2002-1460, April 2002.

[61]Lee, K., and Lee, S. W., "Analysis of Gossamer Space Structures Using Assumed Strain Formulation Solid Shell Elements," AIAA Paper 2002-1559, April 2002.

[62]Johnston, J. D., "Finite Element Analysis of Wrinkled Membrane Structures for Sunshield Applications," AIAA Paper 2002-1456, April 2002.

[63]Wong, Y. W., and Pellegrino, S., "Computation of Wrinkle Amplitudes in Thin Membranes," AIAA Paper 2002-1369, April 2002.

[64]Wong, Y. W., Pellegrino, S., and Park, K. C., "Prediction of Wrinkle Amplitudes in Square Solar Sails," AIAA Paper 2003-1982, April 2003.

[65]Leifer, J., Belvin, W. K., Black, J. T., and Behun, V., "Evaluation of Shear Compliant Borders for Wrinkle Reduction in Thin Film Membrane Structures," AIAA Paper 2003-1984, April 2003.

[66]Su, X., Abdi, F., Taleghani, B., and Blandinao, J. R., "Wrinkling Analysis of a Kapton Square Membrane Under Tensile Loading," AIAA Paper 2003-1985, April 2003.

[67]Cook, R. D., *Concepts and Applications of Finite Element Analysis,* 2nd ed., Wiley, New York, 1978, pp. 353–357.

[68]Tessler, A., Sleight, D. W., and Wang, J. T., "Non-Linear Shell Modeling of Thin Membranes with Emphasis on Structural Wrinkling," AIAA Paper 2003-1931, April 2003.

[69]Kukathasan, K., and Pellegrino, S., "Non-Linear Vibration of Wrinkled Membranes," AIAA Paper 2003-1747, April 2003.

[70]Johnston, J. D., Blandinao, J. R., and McEvoy, K. C., "Analytical and Experimental Characterization of Gravity Induced Deformations in Subscale Gossamer Structures," AIAA Paper 2004-1817, April 2004.

[71]Smith, S. W., Elliott, M. D., Main, J. A., and Clem, A. L., "Post-Flight Testing and Analysis of Zero-Gravity Deployment of an Inflating Tube," AIAA Paper 2001-1265, April 2001.

[72]Black, J. T., Leifer, J., DeMoss, J. A., Walker, E. N., Belvin, W. K., and Smith, S. W., "Experimental and Numerical Correlation of Gravity Sag in Solar Sail Quality Membranes," AIAA Paper 2004-1579, April 2004.

[73]Smith, S. W., and Main, J. A., "Modeling the Deployment of Inflating Space Structures," *Gossamer Spacecraft: Membrane/Inflatable Structures Technologies for Space Applications*, edited by C. H. Jenkins, AIAA, Reston, VA, 2001, pp. 203–241.

[74]Clem, A. L., Smith, S. W., and Main, J. A., "A Pressurized Deployment Model for Inflatable Space Structures," AIAA Paper 2000-1808, April 2000.

[75]Clem, A. L., Smith, S. W., and Main, J. A., "Experimental Results Regarding the Inflation of Unfolding Cylindrical Tubes," AIAA Paper 2001-1264, April 2001.

[76]Clem, A. L., Smith, S. W., and Main, J. A., "Deployment Dynamics of an Inflatable Solar Array," AIAA Paper 99-1520, April 1999.

[77]Welch, A. L., and Smith, S. W., "Experimental Results Regarding Two-Dimensional Deployment of Inflatable Beams," AIAA Paper 2003-1976, April 2003.

[78]Hobbs, K. P., Griffith, T., Smith, S. W., and Main, J. A., "Post-Flight Testing and Analysis of Zero-G Foam Rigidized Struts," AIAA Paper 99-1524, April 1999.

[79]Campbell, J. E., Smith, S. W., Main, J. A., and Kearns, J., "Staged Microgravity Deployment of a Pressurizing Scale Model Spacecraft," *Journal of Spacecraft and Rockets*, Vol. 41, No. 4, 2004, pp. 534–542.

[80]Meyer, C. G., Liefer, J., Lopez, B. C., Jones, D. C., and Caddell, B. C., "Zero- and One-g Comparison of Ripple Amplitude in Single-Curved Parabolic Membranes Using Photogrammetry," AIAA Paper 2004-1736, April 2004.

[81]Bales, G. L., Hall, J. L., Flint, E. M., and Glaese, R. M., "Experimental Issues that Impact In-Vacuum Dynamic Characterization of Thin Film Membranes," AIAA Paper 2003-1743, April 2003.

[82]Salama, M., and Jenkins, C. H., "Intelligent Gossamer Structures: A Review of Recent Developments and Future Trends," AIAA Paper 2001-1196, April 2001.

[83]Ruggiero, E. J., Jacobs, J. H., and Babb, B., "A SPIDER Technology Overview," AIAA Paper 2004-1822, April 2004.

[84]Jenkins, C. H., "In-Situ Manufacturing of Gossamer Spacecraft by Artificial Web-Spinning," AIAA Paper 2001-1493, April 2001.

[85]Quadrelli, M., and Sirlin, S., "Modeling and Control of Membranes for Gossamer Spacecraft: Part 1: Theory," AIAA Paper 2001-1201, April 2001.

[86]Williams, R. B., Austin, E. M., and Inman, D. J., "Local Effects of PVDF Patches on Inflatable Space-Based Structures," AIAA Paper 2001-1198, April 2001.

[87]Baruh, H., "Control of the Elastic Motion of Lightweight Structures," AIAA Paper 2001-1340, April 2001.

[88]Miyazaki-Kawasaki, Y., and Furuya, H., "Static Shape Control of Membrane Structures by Piezoelectric Films Bonded Around Creases," AIAA Paper 2001-1619, April 2001.

[89]Jenkins, C. H., and Schur, W. W., "Gore/Seam Architectures for Gossamer Structures," AIAA Paper 2001-1262, April 2001.

[90]Duvvuru, H., Hossain, N., and Jenkins, C. H., "Modeling of an Active Seam Antenna," AIAA Paper 2003-1739, April 2003.

[91]Gorinevsky, D., Hyde, T., and Cabuz, C., "Distributed Localized Shape Control of Gossamer Structures," AIAA Paper 2001-1197, April 2001.

[92]Tzou, H. S., Wang, D. W., and Chai, W. K., "Dynamics and Distributed Control of Control of Conical Shells Laminated with Full and Diagonal Actuators," *Journal of Sound and Vibration,* Vol. 256, No. 1, 2002, pp. 65–79.

[93]Tzou, H. S., Chai, W. K., and Wang, D. W., "Micro-Actuations and Location Sensitivity of Actuator Patches Laminated on Toroidal Shells," *Journal of Vibration and Acoustics*, Vol. 126, No. 2, 2004, pp. 284–297.

[94]Peng, F., Hu, Y.-R., and Ng, A., "Active Control of Inflatable Structure Membrane Wrinkles Using Genetic Algorithm and Neural Network," AIAA Paper 2004-1827, April 2004.

[95]Jha, A. K., and Inman, D. J., "Sliding Mode Control of a Gossamer Structure Using Smart Materials," *Journal of Vibration and Control*, Vol. 10, No. 8, 2004, pp. 1199–1220.

[96]Sung, Y.-G., "An Estimator-Based Sliding Mode Control for Maneuvering a Flexible Spacecraft," *Journal of Sound and Vibration*, Vol. 256, No. 1, 2002, pp. 155–171.

[97]Glaese, R. M., and Balas, G. L., "Demonstration of Dynamic Tailoring for Gossamer Structures," AIAA Paper 2004-1824, April 2004.

[98]Solter, M. J., Horta, L. G., and Panetta, A. D., "A Study of a Prototype Actuator Concept for Membrane Boundary Control," AIAA Paper 2003-1736, April 2003.

[99]Rogers, C., and Agnes, G. S., "Active Axisymmetric Optical Membranes," AIAA Paper 2002-1450, April 2002.

[100]Sobers, D. M., Agnes, G. S., and Mollenhauer, D., "Smart Structures for Control of Optical Surfaces," AIAA Paper 2003-1559, April 2003.

[101]Flint, E. M., and Denoyer, K. K., "Approach for Efficiently Evaluating Internally Reacted Global Shape Control Actuation Strategies," AIAA Paper 2003-1738, April 2003.

[102]Hoagg, J., Bernstein, D., Lacy, S. L., and Venugopal, R., "Adaptive Control of a Flexible Membrane Using Acoustic Excitation and Optical Sensing," AIAA Paper 2003-5430, Aug. 2003.

[103]Gullapalli, S. N., Flood, R., Yang, E.-H., and Lih, S.-S., "New Technologies for the Actuation and Control of Large Aperture Lightweight Optical Mirrors," IEEE Aerospace Conf., March 2003.

[104]Redding, D. C., Shi, F., Basinger, S. A., Cohen, D., Green, J. J., Lowman, A. E., and Ohara, C. M., "Wavefront Sensing and Control for Large Space Optics," IEEE Aerospace Conf., March 2003.

[105]Witherspoon, S., and Tung, S., "Design and Fabrication of an EAP Actuator System for Space Inflatable Structures," AIAA Paper 2002-1449, April 2002.

[106]Ash, J. T., Jenkins, C. H., Marker, D. K., and Wilkes, J. M., "Shape Achievement of Optical Membrane Mirrors Using Coating/Substrate Intrinsic Stresses," *Journal of Spacecraft and Rockets*, Vol. 41, No. 4, 2004, pp. 551–557.

[107]Gunderson, L. A., Jenkins, C. H., Wilkes, J. M., and Marker, D. K., "Pressure-Augmented near Net-Shape Membrane Mirror," AIAA Paper 2004-1501, April 2004.

[108]Belvin, K., "Advances in Structures for Large Space Systems," AIAA Paper 2004-5898, Sept. 2004.

[109]Dragovan, M., "The DART System for Far IR/Submillimeter Space Telescopes," Highly Innovative Space Telescope Concepts, *Proceedings of the SPIE*, edited by H. A. McEwen, Vol. 4849, 2002, pp. 1–7.

G. Agnes
Associate Editor