Chapter 2: Literature Review

2.1 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 space-born telescopes. Appropriately, the development of an ultra-large, 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 (1995) 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. (2001) assembled a bound volume for AIAA that covers many facets of gossamer technology. The volume consists of twenty-one 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 ultra-large, ultra-lightweight craft.

As a follow-up to the 2001 AIAA volume, Wada and Lou (2002) from the Jet Propulsion Laboratory assembled a review of JPL's pre-flight 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 pre-flight validation procedures. In 2003, Ruggiero et al. (2003) 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 (like polyvinylidene fluoride, or PVDF, and piezo-composite 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 address the specific issues of wrinkle elimination, dynamic control, and membrane shape control in gossamer structures. Over the past 5 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. In this chapter, we 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 may be referred to in this chapter, the references provided should help direct the search of interested engineers and scientists.

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

2.2 Recent Trends in Designing and Analyzing Gossamer Spacecraft

While working for Astro Research Corporation in 1981, John Hedgepeth prepared and submitted a contractor report for NASA Langley Research Center entitled, "Critical Design Requirements of Large Space Structures." In his report, Hedgepeth (1981)

identified early on that "reliability and cost are important factors in a [spacecraft] design" (Hedgepeth, 1981). Therefore, as a consequence, Hedgepeth recognized that ground testing was the link between these two important design criteria, since reliability is proven through pre-flight 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 (1981) 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 ultra-large, ultra-lightweight craft. In 2002, Davis and Agnes (2002) 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 non-linear behavior of membrane optical elements and pressurized parabolic lenses. In 1997, Marker and Jenkins (1997) 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 (2003) recognizes that one of the daunting problems facing ultra-large spacecraft system and control design is the use of ultra-large, often cumbersome models. In his paper, deBlonk develops a model hierarchy to "assess the cumulative effect of modeling assumptions upon solution accuracy and precision" (deBlonk, 2003). 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" (deBlonk, 2003). 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 non-linear region of analysis). A drawback to deBlonk's analysis is that it is based on finite difference methods which may not be able to handle material discontinuities or geometric complexities well if future studies using his proposed method are pursued.

Fang and Lou (1999) 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 pre-tension does demonstrate an out-of-plane stiffness commonly referred to as the differential stiffness. Interestingly enough, 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 (NGST), now known as the James Webber Space Telescope (see Figure 2.1). The authors used a finite element code to look at the dynamic properties of a 32.8 m by 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 Hz, 0.32047 Hz, 0.44065 Hz, and 0.54409 Hz.
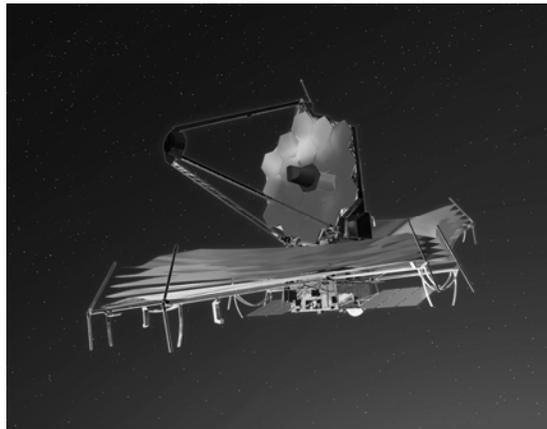

Figure 2.1: A conceptual drawing of the JWST. Drawing courtesy of NASA / Northrop Grumman Space Technology.

The extremely low structural frequencies found by Fang and Lou (1999) 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 designing a gossamer spacecraft or space optic at the system level. In fact, the ultra-flexible 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.

2.3 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, Lassiter, and Ross (2003) 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 ultra-lightweight, ultra-flexible nature of gossamer structures wrecks havoc with traditional dynamic testing techniques. For example, the use of an accelerometer as a dynamic sensor may 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 may puncture or tear the material being tested if the input energy is not properly distributed throughout the structure.

Pappa et al. (2003) 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 Figure 2.2) can be found in Wilkie et al. (2000) and Williams et al. (2002).
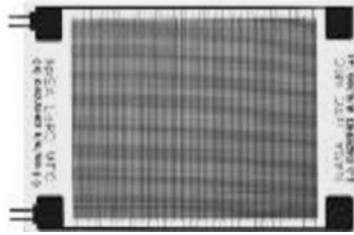
Figure 2.2: A top view of the MFC® actuator (86 mm by 57 mm).

Ruggiero, Park, and Inman (2004) developed an experimental modal analysis technique using multiple MFC® sensors and actuators on an inflated torus. Their proposed MIMO (multi-input multi-output) 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, Bonnema, and Inman (2003) experimentally compared the modal frequencies and damping ratios of an inflated torus with a membrane mirror glued to the interior of the ring (see Figure 2.3). As with Ruggiero, Park and Inman (2004) 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, ultra-lightweight space optic or radar system. For example, in the tests performed by Ruggiero, Bonnema, and Inman (2003) 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 wreck havoc with the structural response of the system. For gossamer technology to mature to a space-worthy technology, such testing issues must be addressed.
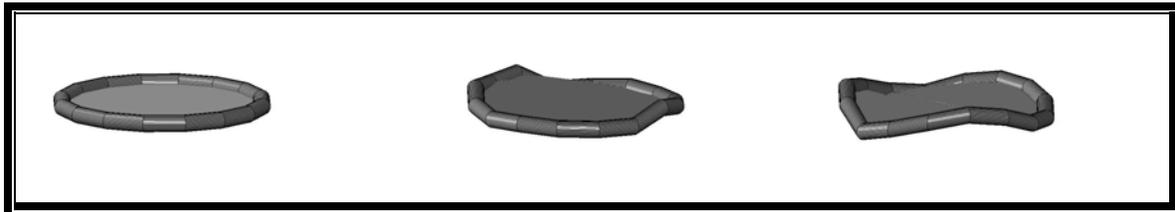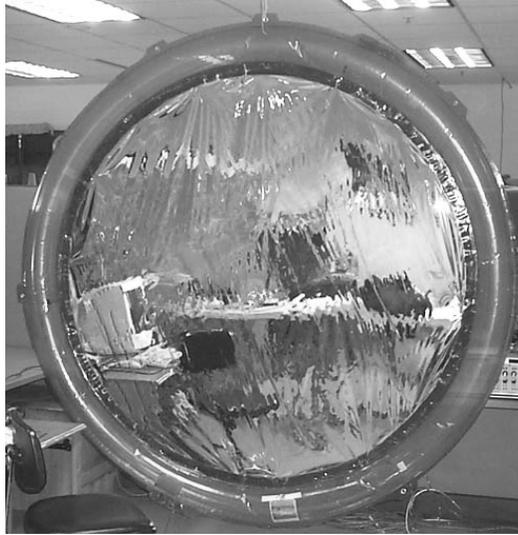
Figure 2.3: Experimentally identified mode shapes of an inflated torus with attached membrane mirror (pictured at top). The torus is shown at rest (left) and vibrating at the first and second out-of-plane modes (middle and right).

Sodano, Park, and Inman (2003) investigated the use of multiple MFC® devices for vibration control of an inflated torus (the same torus as Ruggiero, Park, and Inman (2004)). 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, Park, and Inman (2003) 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 to enhance the multifunctionality of gossamer spacecraft.

Gaspar et al. (2004) 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 set up experiments, a magnetic, non-contact 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 pre-planning for excellent testing setups.

Whites and Knowles (2003) proposed in 2003 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, Lin, and Grahne (1999) 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. Firstly, the packing technique and deployment technique must be identified from the get go as they will drive the system design. Secondly, 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. (2003) performed experimental and finite element research on an inflatable hexapod structure with a tensioned membrane. The hexapod structure contains a 3.8 m diameter torus fabricated from twelve 0.18 m diameter 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 twelve cables 0.101 m long and 9.65×10^{-4} m in diameter. The prototype also contained three tapered struts (as shown in Figure 2.4). Using a scanning laser vibrometer and a single point laser vibrometer as velocity sensors, and two electromagnetic shakers as force inputs, the frequency response functions 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, or ERA (Juang and Pappa, 1985). 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 under-predicted and better testing techniques are necessary for identifying material properties. Experimental testing of inflated struts has been performed by Slade and Tinker (1999).
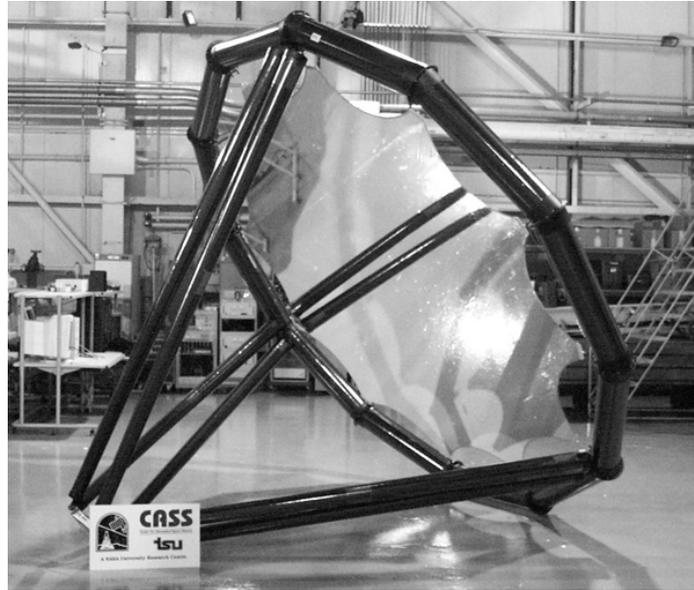
Figure 2.4: The inflatable hexapod structure for dynamic analysis. Photo courtesy of NASA / L. Horta.

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.

Recently, much research has also been performed in the area of photogrammetry—the science of calculating 3D object coordinates from images—for deciphering the rich dynamics of gossamer structures. Photogrammetry and videogrammetry are terms that can be used interchangeably. Pappa, Lassiter, and Ross (2003) 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. (2003)), a 4.5 m inflatable tripod, and three prototype solar sails. Pappa, Black, and Blandino (2003) 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" (Pappa, Black, and Blandino, 2003). Further, depending on the application, the set up of a photogrammetry experiment may 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 Figure 2.5. Johnston et al. (2003) 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.
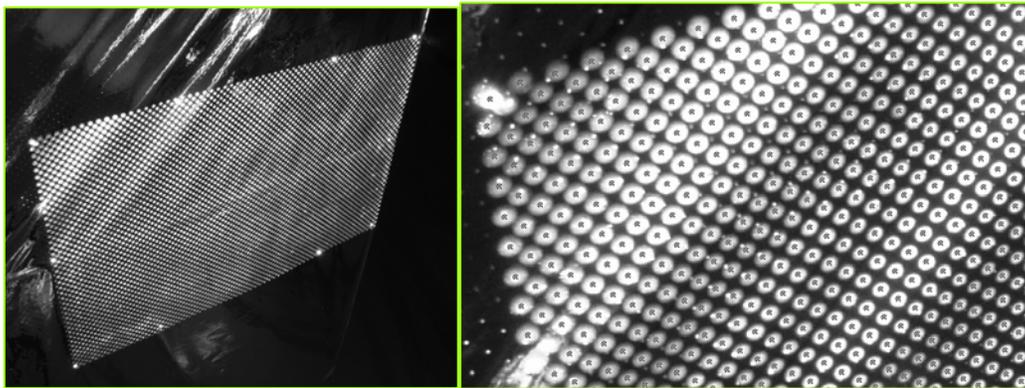

Figure 2.5: A 2 m aluminized Kapton solar sail (left) with applied spot targets for photogrammetric measurements. The upper left corner of the solar sail is magnified at right. Photos courtesy of NASA / R. Pappa.

Pappa et al. (2003) 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 m by 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. Blandino, Pappa, and Black (2003) 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 - $200,000). These efforts were solidified in the results presented by Black and Pappa (2004). On a 2 m solar sail sample, Black and Pappa (2004) were able to demonstrate ± 0.02 mm accuracy (see Figure 2.6).
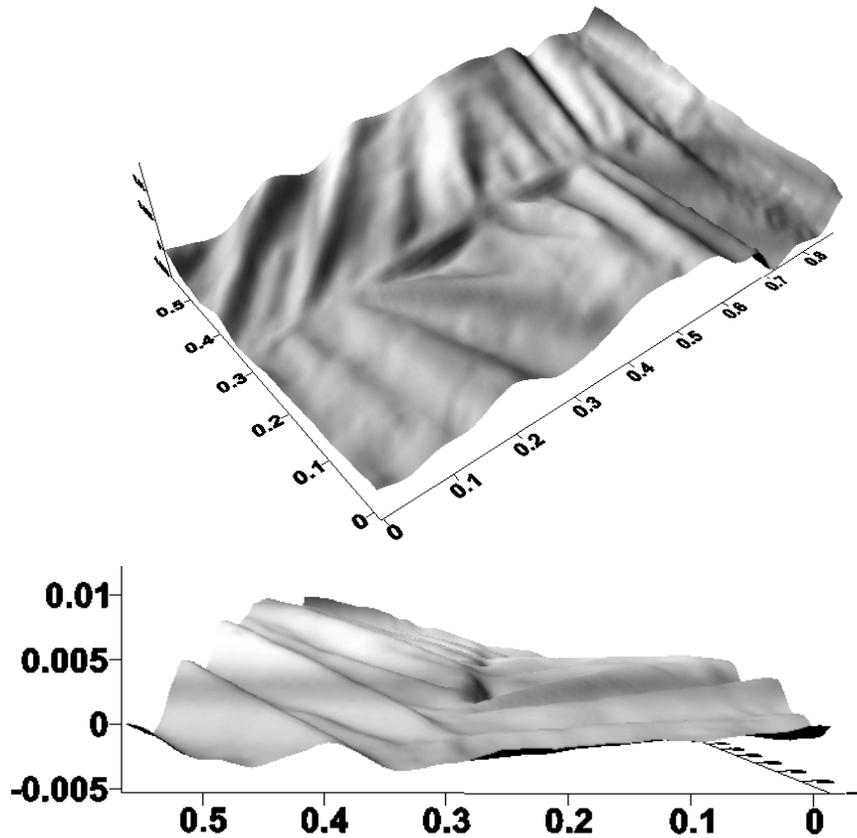

Figure 2.6: Photogrammetry techniques can be used to measure the amplitude and frequency of wrinkles, as demonstrated by a 2 m aluminized solar sail experimental analysis. Figure courtesy of NASA / R. Pappa.

Dorrington et al. (2003) 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 non-invasive, non-contact testing technique that eliminates the need for retro-reflective 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 (2001) 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 CCD 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 (2001) 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, Codagan et al. (2002) 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 (2001) were also interested in the surface accuracy and dynamic response of a stretched membrane sample. Firstly, 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. (2002) 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. (2003) 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 diameter 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 may 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 et al. (2003) looked at a slightly different problem than Flint et al. (2003). 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 non-contact, non-intrusive 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.

2.4 Membrane Mirror Technology Development

Achieving ultra-large spacecraft with ultra-low areal densities mandates the development of membrane mirrors and associated technology. The strict surface tolerance requirement, on the order of a 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 (1977) 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 100V 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 (1994) 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 diameter 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" (Takami and Iye, 1994). 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" (Takami and Iye, 1994). 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. The membrane mirror had a bandwidth of 3.3 kHz. Nearly three decades later, research interests have again peaked in the area of ultra-thin membrane optics.

Although space is a nasty environment for manmade satellites, it does offer some advantages. Bekey (1999) proposed a concept for a revolutionary, ultra-large, ultra-lightweight 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" (Bekey, 1999). 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, Martin, and Nelson (1999) proposed a non-contact 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, Martin, and Nelson (1999) 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 (like 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 (2002) reports that the Lawrence Livermore National Laboratory has been developing techniques for fabricating meter size and larger Fresnel phase plate optics made out of Solar Sail materials. Other authors (Forward, 1984; Chesnokov and Vasileisky, 1997) 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 pathway, and illustrates the Lawrence Livermore Laboratory's capabilities in the manufacturing of amplitude zone plates made of sail materials (Early, 2002).

Dixit et al. (2002), also from the Lawrence Livermore Laboratory, experimentally tested a "50 cm diameter, f/100, 4-level diffractive lens in a fused silica substrate" (Dixit et al., 2002). 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 ultra-large 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 ultra-large space mirrors, the results of Dixit et al.'s experimental work (2002) 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.

2.5 A 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 (1996) 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 non-axisymmetric problems, vibration and dynamic response of membranes, wrinkling, underconstrained pneumatic envelopes, and experimental methods for analyzing the non-linear behavior of membranes. Solar sails, a particular example of gossamer technology that is severely taxed by the formation of structural wrinkles, are summarized in an article by Garner and Leipold (2003).

In 1998, Greschik et al. (1998) 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* (or AM). 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. (1998) 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. (1999) 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 non-linear finite element method in conjunction with a total Lagrangian formulation and convected curvilinear coordinate system (Blandino et al., 2001). 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" (Blandino et al., 2001). Again, as with Greschik et al. (1999), the authors found that including the wrinkling theory in their analysis was critical to developing a stable, proper deployment model.

Murphey and Mikulas (1999) investigated the effect of wrinkles on the in-plane stiffness characteristics of thin films. The authors specify on 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" (Murphey and Mikulas, 1999). Secondly, the authors distinguish *material wrinkles* from *structural wrinkles*, which are caused by "buckling of thin films under compressive stresses" (Murphey and Mikulas, 1999). Further, wrinkles can be classified as either *random* or *systemic*. *Random* wrinkles result from "uniformly crushing a thin film to varying degrees" (Murphey and Mikulas, 1999) 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" (Murphey and Mikulas, 1999). 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" (Murphey and Mikulas, 1999). Further, the authors 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 (2001) develops 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 (2001) 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 (2001) successfully validated their procedure on a wrinkled scale model of the James Webber Space Telescope solar shield.

Yang et al. (2001) proposed a wrinkle modeling technique substantially different than Murphey and Mikulas (1999) 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, non-linear 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, Ferguson, and Funkhouser (2001) 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 microns) 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 pre-determined locations at 15, 45, 75 minutes, and 24 hours 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" (Reynolds, Ferguson, and Funkhouser, 2001). The authors noted a non-linear 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 may 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. (2004) have also looked at the formation of wrinkles but in directionally-tensioned membrane samples. The authors used a non-linear 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, Virgin, and Belvin (2003) 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.

Blandino et al. (2002) investigated the behavior of wrinkles under thermal and mechanical loads. The authors subjected a square Kapton membrane (0.0005 in 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 1.0 in 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 multi-disciplinary approach that must be taken when working with gossamer structures.

Blandino et al. (2003) performed a similar mechanical and thermal loading experiment on a square Kapton membrane. Building upon the work of Blandino et al. (2002), 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 (see Figure 2.7). ABAQUS was able to account for the material wrinkles because of a user-defined subroutine called UMAT (Adler, 2000).
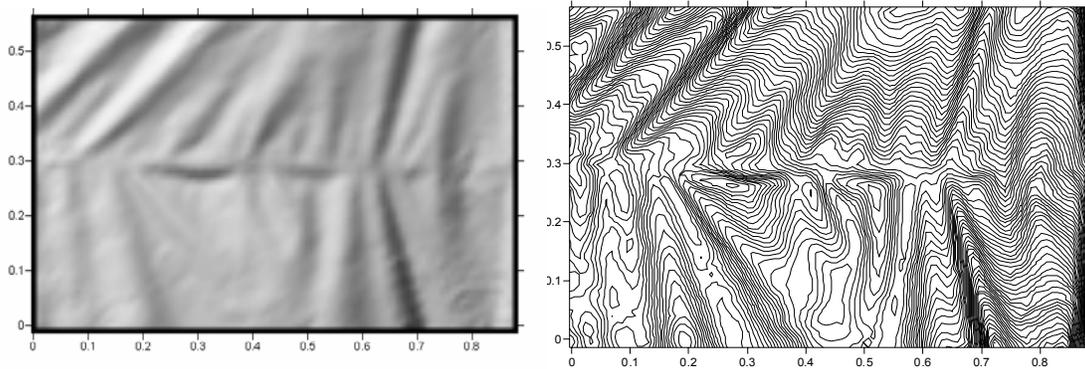
Figure 2.7: Contour plots (left) and topographical maps (right) of a wrinkled membrane sample. Figures courtesy of NASA / R. Pappa.

Ding et al. (2002) proposed a two variable parameter membrane model for the prediction of wrinkles. Similar to Yang et al. (2001), 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 non-linear 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. (2001), 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 (2002) developed a finite element procedure using assumed strain formulation solid shell elements to handle ultra-thin 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 non-linear 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 (2002) 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 Blandino et al. (2003) but originally developed by Adler (2000). 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 $1/10^{\text{th}}$ 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.

Wong, Pellegrino, and Park (2003) 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 degree 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 and Pellegrino (2002), 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. (2003) 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 over 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 square meters 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. (2003) investigated the time evolution of wrinkle development in a square membrane structure using buckling and post-buckling solutions in a software code called GENOA. Their particular code was incorporated with an updated Lagrangian method (Cook, 1978) to account for the non-linear 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, pre-critical load wrinkles.

Tessler, Sleight, and Wang (2003) studied a geometrically non-linear, 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 (2002)). 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, ultra-thin structures.

Kukathasan and Pellegrino (2003) analyzed the non-linear vibration of wrinkled membranes. In a systematic approach, the authors looked at using a finite element 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 was 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. Secondly, 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 $0 - 50$ 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" (Kukathasan and Pellegrino, 2003). 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 non-linearity, and demonstrated the presence of quadratic and cubic non-linearities.

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 may cause structural wrinkles during ground testing that may not be present in space-deployed structures. Johnston, Blandino, and McEvoy (2004) attack the issue of gravity-induced sag through a non-linear 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. (2001) also conducted experimental research to study the effect of gravity on gossamer structures. However, as opposed to the solar sails investigated by Johnston, Blandino, and McEvoy (2004), 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 one-g environment consistently demonstrated a "pressurization delay" during the unfolding process that was not present during their zero-g tests. Follow up work was pursued by Black et al. (2004) 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 (2001), Clem, Smith, and Main (1999, 2000, 2001), Welch and Smith (2003), Hobbs et al. (1999), and Campbell et al. (2004).

Meyer et al. (2004) performed one-g and zero-g experiments on a 1 m scale model parabolic reflector using photogrammetry techniques. They found that in zero-g conditions, surface ripples were less pronounced compared to the one-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 sytem-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.

2.6 Controlling Gossamer Space Structures

Coinciding with wrinkle research has been the development of control methodologies to effectively control both the dynamics of ultra-flexible structures as well as the prevention/elimination of wrinkles from large, ultra-thin lenses. In 1982, Balas (1982) provided a detailed mathematical framework of possible controllers and their incorporation with large space structures. Balas discusses reduced-order models, reduced-order controllers, partial differential equation control and stabilization techniques, adaptive control techniques, and many other control-related topics. His 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 (2001) review recent developments and trends in gossamer space structures. Salama and Jenkins (2001) recognized that the future of ultra-large 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,

or PGAs. 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, Jacobs, and Babb (2004) 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 (2001) 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 may be possible. One of the key technologies identified in the paper are 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 nano-level could be achieved.

In line with Salama and Jenkins' (2001) and Ruggiero, Jacobs, and Babb's (2004) work, several papers have been written addressing some of the key technological pathways to effectively controlling ultra-large space structures. Quadrelli and Sirlin (2001) 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, Austin, and Inman (2001) 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 (2001) 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 (2001) numerically demonstrated static shape control on a folded membrane with piezoelectric film patches bonded along the creases of the folded membrane. The study used membrane theory. 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 (2001) 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, Hossain, and Jenkins (2003) Such technology may 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 space-born optic.

Gorinevsky, Hyde, and Cabuz (2001) 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, Wang, and Chai (2002) 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, Chai, and Wang (2004) 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 micro-level control of a toroidal skin, and is fundamental to the future of integrated smart structures and gossamer spacecraft.

Peng, Hu, and Ng (2004) 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 (2004) designed a sliding mode controller to control unwanted dynamics of an inflated torus. The inflated torus is a possible boundary constraint for ultra-large 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 (2002) 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 degree roll maneuver and maintain line-of-sight tracking with an extended antenna.

Glaese and Balas (2004) researched the area of dynamic tailoring with regards to ultra-flexible 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 discreet 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 narrow-band disturbances. The overall demonstration of vibration attenuation and control by the research team provides strong example that vibration identification and control with ultra-light, ultra-flexible gossamer structures through the use of integrated smart material systems is indeed a viable option.

Solter, Horta, and Panetta (2003) 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. (2003)). 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.

2.7 Controlling Ultra-lightweight Space Optics

Some researchers of late have focused their efforts on trying to actively control the mirror or aperture of an ultra-flexible spacecraft. Rogers and Agnes (2002) 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, Agnes, and Mollenhauer (2003) followed up the work performed by Rogers and Agnes (2002) 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 GE 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 (2003) 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 may prove quite useful, as the prescribed requirements for sensors and actuators may spur technological advancements in this area.

Hoagg et al. (2003) 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 non-linear actuator) or an electron gun (which requires significant secondary structures and precision components).

Gullapalli et al. (2003) provide research on the use of nanolaminate technology to construct near-net shape, optical quality, and ultra-lightweight 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. (2003) suggest the use of a newly designed inchworm actuator (250 micron 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. (2003).

Witherspoon and Tung (2002) investigated a MEMS-based flexible sensor and actuator system for static shape control and structural health monitoring of a gossamer structure. The authors' research looked at using Electro Active 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 space-worthy missions, and further research to improve EAP materials is essential.

The U.S. Air Force has shown considerable interest in the area of ultra-large, ultra-light membrane optics. Recent efforts funded by the Air Force Research Lab have concentrated on the development of near-net shape membrane mirrors that can deploy to optical precision. Ash et al. (2004) 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. (2004) followed up with Ash et al.'s (2004) work by applying pressurization to an under-compensated, 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.

2.8 Chapter Summary

An overview of recent advances in lightweight, ultra-large satellite technology has been presented. Modeling and experimental work in the areas of membranes, membrane wrinkles, and composite systems has been discussed. Further, control systems and algorithms that have been attempted for these unique structures.

The current work will look at developing physics-based models that govern the dynamics of membrane-type lens or aperture structures that have been integrated with piezoelectric material for vibration control. We will step through, systematically, the development of a 1-D model (with experimental verification) and then expand these results to 2-D. But first, we must define some key concepts in terms of variational methods and the finite element method. The next chapter looks at these methods for a simpler example problem in detail.