Integrated Modeling for Lightweight, Actuated Mirror Design

Doctoral Thesis Proposal

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Abstract

Lightweight, actuated mirrors are an enabling technology for large aperture, space-based optical systems. These mirrors have great potential to increase the optical resolution and sensitivity beyond what is currently possible. However, as with all technology development programs, there are remaining issues to be solved before such mirrors can be used in operational systems. As of yet, no efforts have been made to explore the design space or optimize the design of lightweight mirrors across operational environments and constraints. The extremely harsh launch environment is of particular concern because launch survival constraints could dictate aspects of the mirror design.

The objective of this thesis is to develop and validate a methodology for modeling, optimizing, and thereby guiding the design of lightweight actuated mirrors through the use of integrated modeling. Specifically, the launch environment will be modeled to determine limitations on lightweight mirror technology for survival, and launch load alleviation techniques will be analyzed for feasibility and implemented in the model to determine potential benefits. Furthermore, the launch model will be combined with a model for operational performance, in terms of correctability and residual wavefront error, to create an integrated modeling tool for mirrors and mirror control systems. The model will be used as a source of corporate knowledge for mirror design as well as to determine technology limitations and guidelines for lightweight mirror design.

A literature review reveals applicable works from a number of related fields. Literature on telescopes and mirrors, modeling and optimization, controlled structures, and launch loads are of particular interest and have been identified. Additionally, an approach to achieve the proposed objectives is included, along with a schedule, outline, and potential thesis contributions.

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1 Introduction

The next generation of space-based imaging systems will push the limits of current technology and design methodologies, while achieving performance that has previously been impossible. Whether the goals are Earth imaging systems with better ground resolution and located in higher orbits, or astronomical telescopes looking back into time, the desired increase in optical resolution can be obtained through the use of larger primary apertures. However, larger apertures bring about a number of design challenges including mass, volume, and flexibility. Mirrors larger than about three meters in diameter encounter packaging constraints due to the volume of the launch vehicle shroud. Also, mass-to-orbit is limited and extremely expensive, requiring the areal density, or mass per unit area, of the mirrors to decrease as the diameter increases in order to maintain an acceptable launch mass. Furthermore, the large size and the lower mass combine to significantly increase the flexibility of the mirrors, lowering flexible mode frequencies and making them more susceptible to static and dynamic distortion, so maintaining optical tolerances across the mirror surface becomes increasingly difficult. While these challenges are immense, they can be dealt with through the use of lightweight, actuated, segmented primary mirrors. Instead of the traditional monolithic design, the primary aperture is made up of multiple smaller mirror segments which are easier to manufacture and can deploy from a stowed configuration that will fit within a launch vehicle. Furthermore, the mirrors can be rib-stiffened to achieve low mass while maintaining adequate stiffness, and the ribs can contain embedded actuators to control the shape of the mirror to optical tolerances. The size of the achievable apertures and hence the potential imaging resolution are very promising.

As with many promising new technology developments, lightweight, actuated mirror segments solve one problem (aperture size), but introduce a new set of challenges that must be addressed. One issue that arises is the ability to design the mirror to accommodate multiple environments and disturbance sources in an efficient way. For example, launch survival is a key challenge in the mirror design. Launch is an extremely harsh environment and silicon carbide, which is the selected material for this thesis, is a brittle material that could break at low areal densities when exposed to the vibrations and acoustics from launch. Yet it is imperative that these fragile optical components arrive on orbit undamaged. Once on orbit, the mirror design must also meet tight optical performance requirements, in the form of low wavefront error, in the face of static and dynamic disturbances during operation. However, initial analysis indicates that designing a mirror to best accommodate either launch survival or low wavefront error would result in different mirror designs. Therefore, the mirror structure and control system design must be carefully analyzed and optimized in an integrated fashion in order to advance the state of the art in actuated mirror design.

This thesis focuses on the design and optimization of lightweight mirrors, specifically with respect to the launch and operational environments, resulting in an integrated design methodology, which can in turn be used for technology optimization and advancement. This will ultimately lead to increased capabilities of space-based imaging systems.

1.1 Space Based Imaging Systems

Space based imaging systems provide a number of benefits that cannot be gained from ground-based systems. Astronomical space telescopes have the potential to greatly expand our knowledge of the universe, and have a view that is unobstructed by the distortions of the Earth's atmosphere and avoid atmospheric absorption. Earth imaging telescopes provide knowledge about our planet that is simply unattainable through ground-based systems.

Astronomical space telescopes contribute vastly to the understanding of the universe. The Hubble Space Telescope, launched in 1990, images from ultraviolet to near-infrared wavelengths and has provided an immense amount of scientific data. Hubble has helped to determine the age of the universe, improved understanding of planet formation, and discovered extra-solar organic matter, among numerous other accomplishments [96]. The James Webb Space Telescope (JWST) will continue the tradition of large, orbiting observatories [70]. JWST is scheduled to launch in 2013 and will use infrared imaging to provide data that will help scientists understand the Big Bang theory. With its 6.5 m diameter segmented primary mirror, it provides greater mirror design challenges than Hubble, whose primary mirror measures 2.4 m in diameter.

Earth observation systems can be used for Earth imaging, climate change, national security, and other applications. A history of Earth observation can be found in Kramer [63]. For example, the LandSat program [105] has been running since 1972 and is a resource for global change research in fields such as geology and agriculture. Recently, commercial imaging systems such as IKONOS [3] have also been successful, with new commercial imaging satellites including DigitalGlobe's Worldview-1 [4] and GeoEye's GeoEye-1 [2] having recently launched in September 2007 and September 2008, respectively. These new commercial systems have ground resolutions as fine as 40 cm, with the largest primary aperture being 1.1 m in diameter [59]. It is worth noting that, even with the increased capabilities of the new commercial systems, commercial imaging systems are generally significantly smaller than their government funded counterparts, particularly the large space observatories such as Hubble and JWST.

Given the success of space-based optical systems, the question becomes what capabilities and technologies will enable the next generation of space-based imaging systems. The next logical steps are to continue to increase the aperture size to reap the benefits of the increased resolution capabilities [13]. However, the areal density, or mass per unit area of the primary mirror, must decrease to keep the mass and costs feasible. NASA has developed a capability road map to address the technologies that are necessary to enable the next generation of envisioned space telescopes and observatories [93]. These technologies include optics, wavefront sensing and control, distributed and advanced spacecraft systems, large precision structures, and cryogenic and thermal control systems. In the realm of optics, the following technology goal is stated: "Lightweight affordable optics is an enabling capability for future large-aperture space optical systems for Earth science, solar observations, and astronomy" [93]. This motivates the development of lightweight, actuated mirror segments as a potentially affordable approach to achieving larger aperture systems.

1.2 Lightweight Mirrors

Lightweight mirrors are necessary to be able to launch larger apertures. The Hubble mirror has an areal density of 180 kg/m^2, yielding a total mass of 720 kg for the 2.4 m diameter mirror. Mirrors this massive are expensive to launch, and scaling the high areal density to a larger diameter system is impractical. Therefore, mirrors must become lighter to increase their size. Light-weighting can be achieved by removing unnecessary material from the back of the mirror, resulting in a rib-stiffened back structure that can maintain structural stiffness at a lower mass. However, rib-stiffening has limitations and, as the areal density decreases, the flexible mode frequencies will decrease, making the mirrors more susceptible to deformations, leading to thermal, dynamic and manufacturing distortions. To counteract these errors, actuation can be used to control the mirror surface to optical tolerances, increasing the possibilities in mirror design by allowing lower mass systems to meet performance requirements.

A number of material options exist for lightweight mirrors, including glass, beryllium, and silicon carbide, as discussed further in Section 3.1. Traditional mirrors have been made from glass, though glass is difficult to form and polish leading to long manufacturing times. Furthermore, glass mirrors can be manufactured with areal densities as low as about 15 kg/m^2, but cannot be decreased further. Beryllium has high stiffness, low mass, and is stable at cryogenic temperatures, which are good qualities in optical materials. However, beryllium is toxic and limited in supply. Actuated silicon carbide (SiC) mirrors provide a promising path for a number of reasons [27, 62]. Silicon carbide mirrors can be more quickly formed and some of the lengthy polishing process can be replaced with actuation that reduces distortion. Furthermore, compared to glass, SiC's higher strength allows larger strains, simplifying actuation and making the mirror more correctable. SiC also has a high thermal conductivity, reducing thermal gradients that can be a significant source of deformation.

However, there are also a number of issues with actuated SiC mirrors that need to be resolved. First, there can be manufacturing errors from a number of sources, including print-through, which is a high spatial frequency error resulting from the non-uniformity of the stiffness and the polishing process, leading to errors in the mirror with the same spatial frequency as the rib structure. Dimpling is another source of error, and refers to uncontrollable, high spatial frequency error that is induced by actuating low spatial frequency shapes. Also, SiC has a high coefficient of thermal expansion (CTE), which causes deformations due to temperature changes which must be counteracted with actuation. Additionally, actuator channel count complexity becomes an issue as the number of actuators that are embedded in the mirror increases. Finally, launch survival is of significant concern, especially as the areal density decreases. Each of these issues drive the mirror design in different directions, but a single mirror must be used in all situations.

A great deal of work has been done on advancing the silicon carbide mirror technology, particularly in the areas of manufacturing, and necessary supporting equipment such as wavefront sensing. However, relatively little attention has been paid to the design implications of designing a mirror for the many issues facing mirror design, such as low spatial frequency actuation, minimization of high spatial frequency errors, vibration suppression, thermal distortions, and launch stress. Designing a mirror to best accommodate launch survival, correctability of focus, or minimization of high spatial frequency error would result in three different mirrors, which is clearly not possible, motivating an integrated design methodology for lightweight actuated mirrors.

2 Problem Statement and Objectives

The use of lightweight, actuated, silicon carbide mirrors for space-based optical applications has clear benefits. However, it also introduces a number of challenges and issues. Therefore, it is essential to have the ability to analyze and optimize the mirrors for both survival during launch and performance on orbit.

In order to advance the state of the mirrors, it is preferable to explore the trade space and optimize the design, rather than choosing point designs. Therefore, an integrated modeling framework is used to quickly create entirely new, distinct mirror models for analysis. With this methodology, the families of favorable designs, as well as the parameters to which the design is most sensitive, can be identified. Parameters can also be varied in support of uncertainty analysis. Furthermore, test data and lessons learned can be incorporated into the model, so that it is an archive of corporate knowledge as well as a tool for future system design.

There are a number of issues related to the mirror design. First, the ability of the mirror to survive launch can be greatly influenced by the design of the mirror. Survivability can be augmented by isolation or other methods, but the design of the mirror is a significant contributor. Additionally, the operational imaging performance, in terms of wavefront error, is largely dependent on the mirror design. Both of these areas contribute to the overall performance of the mirror, and are described in more detail below.

Launch Survivability Launch is an extremely harsh environment, and launch survival can dominate many aspects of design. Therefore, it is desirable to identify and understand the implications and limitations of design parameters (such as areal density and rib geometry) on launch survival. Furthermore, attenuating launch vibrations using isolation, as well as active and passive damping using the embedded actuators, is of significant interest. Therefore, one aspect of this thesis is to examine the mirror design from the launch perspective to ensure survival.

Operational Performance Requirements Once on orbit, the primary objective of the mirror is imaging. A metric for imaging quality is the amount of residual wavefront error (WFE) in the mirror after the control is applied. The finite length and spacing of the actuators causes a uncontrollable high spatial frequency residual error when actuating a lower spatial frequency shape. Additionally,the mirror design is also influenced by the correctability of the mirror in response to thermal or dynamic disturbances or manufacturing imperfections. The correctability, or range of shapes which can be achieved using the embedded actuators, is the second metric for operational performance.

While there has been previous work on modeling and multidisciplinary optimization, optimization of actuated mirror design involves challenges that make it a unique problem. First, the mirror must perform well, in terms of meeting performance requirements and constraints, under multiple types of disturbances. Next, it is a controlled structure, which increases complexity due to the interaction of the structural design and control system. Additionally, it is an extremely high precision system, with wavefront error requirements on the order of nanometers. This type of precision over the large area of the mirror significantly increases complexity, making it necessary for models to have high spatial and temporal bandwidth, and requiring both high order model fidelity and accuracy. Also, the system is inherently multidisciplinary, including controls, structures, thermal, optics, disturbances, modeling, and uncertainty, which must all be considered simultaneously. Finally, the analysis requires high fidelity models to capture the characteristics of the system, but it is difficult to do optimization with high order models due to computational expense. Therefore, the challenges involved in design and technology maturation of actuated, lightweight mirrors presents a rich and unique area of research.

2.1 Problem Statement

Given the benefits and challenges of actuated, lightweight mirror technology, the question becomes: how do you design a mirror that will *survive launch* and *perform well* on orbit, in terms of wavefront error and correctability? Furthermore, how do you determine those designs in an efficient manner, with constrained amounts of money and time? The hypothesis is that this may be accomplished through the use of integrated modeling and multidisciplinary optimization, with models that will incorporate test data and other developmental experience. Consequently, the model will become a key component in guiding technology development as well as qualifying mirrors for flight. Moreover, the methodology developed herein will prove useful for other precision opto-mechanical systems.

2.2 Scope

The technology development for lightweight, actuated mirrors is an extremely large topic. Therefore, the scope must be limited to ensure a problem with a feasible size. First, only issues pertaining to the *mirror design* will be considered. Therefore, any issues with manufacturing, telescope design, mission, etc. are outside of the scope of this work. It should be noted that these other issues are important and will need to be considered and addressed, though their impacts can be assessed through a secondary analysis. Also, manufacturing constraints such as minimum rib thickness will be imposed on the design. Second, there are a number of different environments/disturbances that could affect the mirror. Many of these disturbances either (1) result in small errors compared to other sources or (2) could be counteracted through other, more traditional techniques. For example, reaction wheel imbalance results in dynamic jitter of the telescope system. Rather than mitigating this vibration with the embedded actuators in the primary mirror, it is possible to use a fast steering mirror farther down in the optical train to correct for the jitter, resulting in a much less complex solution. Therefore, by applying these criteria to the various factors in the mirror design, the scope of this thesis is to model and analyze mirrors considering the following:

- Launch load analysis and alleviation

- High spatial frequency residual wavefront error (errors with spatial frequencies above the spatial frequency of the actuators)
- Correctability (amount of shape change that can be achieved through actuation)

This combination accounts for the major areas of mirror design, without introducing unnecessary scope to complicate the problem.

In considering these various objectives, a number of modeling and optimization techniques will be used. The error sources will be combated using a set of tools, including (1) structural design and (2) control systems, isolation, and damping augmentation. Therefore, the focus on control system design is not in the development of new algorithms or the optimization of control gains, but rather in the use of controls as a tool to achieve the necessary performance in the presence of uncertainty. Furthermore, existing modeling, reduction, numerical conditioning, and optimization techniques will be exploited and augmented with new approaches as necessary. By limiting the number of disturbance environments and performance outputs, using design and controls as tools, and using existing modeling and optimization techniques when appropriate, the scope of the mirror design problem is limited to a reasonable size, while still providing valuable information about actuated mirror design and design methodologies for technology maturation programs and model-based flight qualification.

2.3 Thesis Objectives

The objective of this thesis is to develop and validate a methodology for modeling, optimizing, and thereby guiding the design of lightweight, actuated mirrors through the use of integrated models.

1. Develop an integrated modeling tool for lightweight mirrors and mirror control systems.
    - Develop a finite element and state space model of an actuated, silicon carbide mirror segment.
    - Model the vibroacoustic launch environment.
    - Create quasi-static control algorithms for shape control of the mirror during operations, including models for correctability and residual high spatial frequency wavefront error after application of control.
    - Validate the model using available data and simple problems.
    - Define the baseline mirror design parameters.

2. Characterize the limitations of lightweight, actuated, SiC mirrors in different environments, specifically, correctability, high spatial frequency error, and launch survival.
    - Define the minimum performance requirements and margins of safety.
    - Assess the baseline mirror against those minimum performance requirements.
3. Identify favorable actuated lightweight mirror architectures through trade space exploration and optimization, where favorable is characterized by the peak launch stress, high spatial frequency error, correctability, mass, and actuator channel count.
    - Perform single axis trade analyses to assess the effects of the design parameters.
    - Model launch load alleviation techniques, including isolation systems, passive damping using shunted piezoelectrics, and active damping using robust control methods with the embedded actuators.
    - Reduce and numerically condition the model.
    - Assess the separable design problem by designing a mirror to perform best in each of the three situations (launch survival, correctability, and high spatial frequency residual error).
    - Assess and optimize the coupled design, accounting for all environments together.
4. Illustrate a procedure for capturing developmental experience, including test data, over the life cycle of such a model, and show how to use the model and optimization to guide future development.
    - Demonstrate the chronological nature of the design process in technology development, and how the evolution of the model contributes to the design.
    - Show how to use the model and optimization to find families of strongly performing design in order to guide development.

3 Literature Review

The work proposed herein draws on a number of areas of literature. These can be assembled into a few major categories: telescopes and mirror design, modeling and optimization, controls and controlled structures, and launch analysis. These areas encompass the bulk of the material that is pertinent to this thesis, and include relevant portions of the fields of optics, structures, controls, structural dynamics, disturbance analysis, and optimization.

3.1 Telescopes and Mirrors

There is a large amount of literature concerning telescopes and mirror design. The applications are numerous and the scientific possibilities are abundant, as described briefly in Section 1.1. There exist capability road maps [93, 103] that discuss the technological advances necessary to make future concept missions a reality, including the development of large, lightweight optics. The scientific benefits of large aperture imaging systems, as well as the stated desire to develop lightweight optics capabilities to achieve large aperture systems clearly motivate this work.

Future space telescope concepts are trending toward utilizing more actuation to meet performance requirements. Lillie and Bronowicki [65] propose achieving optical performance requirements by using actuated mirror mounts and passive isolation. MacEwen [69] goes a step further and discusses using embedded actuation in the mirror to similarly achieve optical performance at low areal densities. Ealey [28] proposes moving toward actuation in the entire telescope system for achieving the desired performance. As these future architectures trend toward increasing flexibility and control, more integrated modeling is required to ensure success. The current state-of-the-art in space telescope development is JWST. JWST uses actuation of the rigid body motion of the mirror segments, and has an extensive modeling effort associated with its development [81]. Models for many subsystems, such as thermal, optics, and structures, are combined in order to calculate the performance of the system [48, 52]. However, the modeling is largely of the single chosen point design, with limited opportunities for changing design variables to explore alternate, potentially better performing architectures.

Large ground telescope systems also undergo significant modeling efforts. Ground telescopes face fundamentally different issues than space telescopes. Launch weight and volume are no longer restricted, and, instead, the mirror size constraint is due to manufacturability, gravity sag, and the size of the enclosure. Furthermore, since weight is less expensive on the ground, the mirrors can use heavier surface-normal actuation, where the actuators are normal to the surface and push against a massive back structure to control the shape of the mirror. Despite these differences, large ground telescopes are precision, opto-mechanical systems, and space telescopes could use similar modeling efforts as these ground-based systems. Angeli et al. [6, 7] are developing an integrated modeling environment for cost and performance predictions for large, ground-based telescope systems. They advocate versatile models that can be used for design and can accurately predict relevant performance parameters under typical disturbances. The flexible modeling environment for design is a step toward using integrated modeling early in the design process as a way to determine the system architecture, as is proposed herein.

In addition to integrated modeling for telescopes, the development of lightweight mirrors and their corresponding actuation systems is pertinent to this work. Lightweight mirrors are imperative to the ability to launch systems with larger apertures, and are most often built by eliminating mass from the back side of the mirror and creating a rib structure which maintains stiffness. The Hubble Space Telescope mirror has an areal density of approximately 180 kg/m^2 and is made of glass. The JWST mirror, as discussed in Stahl [92], will achieve an areal density of 26.5 kg/m^2 and is made of beryllium, which will be state-of-the-art for space-based systems. During the initial development of JWST, a number of potential mirror materials were examined as a part of the Advanced Mirror System Demonstrator (AMSD) program. The AMSD effort, described in more detail in Mayo [75], examined many materials in Phase 1, and eventually down-selected to three designs: Kodak's ultra-low expansion (ULE) glass mirror [74], Ball Aerospace's beryllium mirror [60], and Goodrich's fused silicon mirror [33]. Ultimately, beryllium was chosen for JWST for its stiffness and ability to maintain optical stability in the cryogenic thermal environment in which JWST will operate. However, there are a number of issues with beryllium, such as limited availability and toxicity, that suggest continued investment in other mirror materials and technologies. Therefore, in general, glass is likely the best option for areal densities of 15 kg/m^2 or above, and silicon carbide and composite mirrors provide the most promise for attaining lower areal densities, as discussed in Matson and Mollenhauer [73] and Kasl and Crowe [58]. Burge, Angel, Miller et al. [16, 17, 78] have developed lightweight glass mirrors through the use of a glass membrane on an actuated support structure. These mirrors have been manufactured up to 2 m in diameter, and can theoretically be scaled to as large as 6-8 m in diameter, while achieving areal densities as low as 15 kg/m^2. However, they will require a great deal of active control to maintain optical tolerances and extremely large mirrors are difficult to manufacture and launch. Ealey [29, 27] and Kowbel [62] both discuss the properties of silicon carbide (SiC) that make it an attractive material for large, very lightweight optics, such as high stiffness, high fracture toughness, and high thermal conductivity. Ealey goes on to discuss both the challenges and benefits involved in manufacturing SiC mirrors. SiC mirrors are often cast, which is a replication process that can save time and money when multiple mirror segments are manufactured. The benefits of SiC will result in continued attention to it as an optical material; however, SiC mirrors will need to be actuated to achieve the optical performance requirements.

The actuation of SiC mirrors necessitates the field of active and adaptive optics. Active and adaptive optics refer to optical components whose characteristics are controlled during operation to modify the wavefront, with the difference being the bandwidth of the control. Adaptive optics typically refers to high bandwidth, and active optics generally refers to low bandwidth or quasi-static control, though the terms are occasionally used interchangeably. Active optics has been used since the 1950s; Hardy [44] presents an overview of early developments in the field. Adaptive optics were first used on ground based systems to counteract the "twinkling" due to atmospheric turbulence [97], and was implemented using deformable mirrors in the optical train as tertiary, or later mirrors. Freeman and Pearson [31] present a review of deformable mirror technology. Active optics can also be used in a segmented primary mirror to control the piston, tip, and tilt of each mirror segment, as well as to control the figure of the mirror surface, as proposed by Robertson [86] in 1970. Quasi-static shape control has continued to receive attention over the years, and is generally accomplished through the use of influence functions, which are the measured effect of each actuator on the mirror surface figure. Furber et al. [32] developed a correctability model of a one-meter ULE glass mirror segment through the use of finite element modeling (FEM) for the purpose of investigating the effect of the number of actuators on correctability, and Shepherd et al. [89] have compared FEM results to test articles for achieving quasi-static shape control. Additionally, Jordan [54, 53] used integrated modeling to investigate athermalization of an actuated mirror through the use of embedded sensors, and Gray [38] investigated the residual high spatial frequency error due to shape control. The work proposed herein will directly build upon the initial work of Jordan and Gray.

A great deal of work has been done on telescope modeling, both for ground and space based systems. Also, lightweight mirrors and their active optics systems are being developed and improved, with research focusing on optical material selection, manufacturing techniques, wavefront sensing and control, and actuator design. However, there are a few key areas of literature that are lacking from lightweight mirror design, including optimization of the lightweight mirror system and analysis of the effects of launch. This thesis will help to fill those gaps in the literature, advancing the field of lightweight, actuated mirror design.

3.2 Modeling and Optimization

Modeling, simulation, optimization, and the design process are critical to the development and design of any complex system. Specifically, literature pertaining to integrated modeling, multidisciplinary optimization, model reduction, and validation is related to this work and discussed below.

Parametric, integrated modeling refers to modeling of systems containing multiple disciplines in such a way that design variables are parameterized and can be easily changed to create new models. It has been shown to be useful for a number of different applications, and particularly during the conceptual design phase of a program. A number of such applications are discussed in Uebelhart [99], and include the automotive and aircraft industries. The Modular Optical Space Telescope (MOST) project, upon which this work is built, has done significant work on parameterized, integrated modeling for trade space exploration, as summarized in References [101, 55, 100, 20]. Of particular interest, Uebelhart [99, 102] looks at the benefits of integrated modeling and uncertainty analysis early in the design process while using a modular software environment. There have also been a few instances of fully parameterized integrated modeling for space systems. Jilla [51] uses parametric integrated modeling for Terrestrial Planet Finder (TPF), but with significantly less detail than is necessary for detailed mirror design. Lobosco [67] uses an integrated model of TPF Structurally Connected Interferometer (SCI) with a few variable structural parameters, but again without the full set of structural and control parameters considered here. Additionally, as cited above, JWST extensively used integrated modeling [81, 48, 52, 25] in the design, though it is used on the chosen point design, rather than in a parameterized way during conceptual design.

In addition to model development, there has also been progress in developing integrated modeling environments. The Disturbance, Optics, Controls, and Structures (DOCS) [15, 68] toolbox provides a way to combine different disciplines in a Matlab environment. Similarly, Genberg et al. [34, 35] have combined optical modeling programs such as Code V with Nastran through a tool called Sigfit for integrated opto-mechanical modeling. Tools such as these simplify the modeling process by easing the integration of multiple types of models, and DOCS will be used in this work. Parametric, integrated models and modeling environments are particularly useful in optimization and have been successful in other fields, though use has been thus far limited in space applications.

Multidisciplinary optimization (MDO) involves using optimization across disciplines and at the system level, rather than the subsystem level, and is a natural progression to maximize the benefits of integrated modeling. An overview of the field of MDO can be found in Sobieski and Haftka [91], which reviews modeling for MDO, approximation methods, sensitivity, as well as examples of MDO in aerodynamic/structural optimization and aerospace structural/control optimization. While the overall field of MDO is large and growing rapidly, MDO techniques as applied to opto-mechanical systems represents a significantly smaller set of literature. Haftka [42] and Onoda and Haftka [84] have used MDO techniques to simultaneously optimize structural and control parameters for space structures. Jilla [51] used multiple MDO techniques to optimize the conceptual design of a distributed satellite system. De Weck [26] used MDO to find pareto-optimal points satisfying achievable isoperformace characteristics for precision opto-mechanical systems. Finally, Cullimore et al. [24] combined commercial structural, thermal, and optical software packages in order to use MDO for a space telescope design to demonstrate the benefits of such an option. These works represent progress toward using MDO in space applications and provide a point from which to begin this work. However, MDO has yet to be applied to lightweight mirror systems.

A potential difficulty with MDO in mirror systems is the computational expense, as the mirror models must be high fidelity to capture the intricacies of the design and control. Model reduction and approximation methods can be used to decrease the size of a model to make optimization possible. Model reduction can be done in a number of ways. A popular way is balanced truncation, as originally proposed in Moore [80] and further discussed in Pernebo and Silverman [85] and Uebelhart [98], among others. There are a number of difficulties that balanced truncation can encounter, such as difficulties calculating grammian matrices, which describe the amount that states are controllable or observable, and numerical ill-conditioning. Therefore, a number of methods have subsequently been developed to make balanced truncation more widely applicable. One such method presented by Willcox and Peraire [104] uses proper orthogonal decomposition to approximate the grammians. In addition to reduction, Barthelemy and Haftka [11] provide a review and analysis of a number of approximation concepts, including local, medium range, and global approximation concepts for structural optimization applications. Robinson [87] discusses surrogate-based optimization where a low fidelity model is used for the majority of the optimization, with occasional checking of the high fidelity model for accuracy. Furthermore, the symmetry of the mirror system can be exploited to reduce the order of the model. Circulant symmetry can be used to block diagonalize the system such that it can be analyzed as a much smaller system, and is described in Wall [56] and Grocott [41]. Model reduction can be done in a variety of ways, and the type of model reduction to use depends heavily on the type of model being considered. This work will attempt to draw upon the existing model reduction and approximation techniques summarized above, but may modify or build upon them as necessary.

Model validation and verification (V&V) is an important aspect in any model-based design. According to AIAA [1], Verification is the process of determining that a model implementation accurately represents the developers conceptual description of the model and the solution to the model. Validation is the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model. Balci [10] presents an overview of validation, verification, and testing techniques that are available for use. Space telescope and mirrors are extremely difficult to test on the ground, which limits the amount of model validation that is possible. To address this issue, a number of efforts have been undertaken to ensure that the system will function despite this difficulty in testing. Babuska, Carter, and Lane [9] discuss the

Structural Vibration Modeling and Validation (SVMV) program with the goal of addressing exactly this issue, and suggest robust control methods, which are functional, despite their performance set-backs. Robust control will be revisited in Section 3.3. Masterson and Miller [71, 72] use dynamic tuning to modify the system on-orbit. If the system is designed to be tuned after it is launched, then it can accept more uncertainty than an untunable system, eliminating some of the ill effects of uncertainty in the model. Finally, Kerley et al. [61] discusses the validation of the integrated model for the Thirty Meter Telescope (TMT), which is a complex, opto-mechanical simulation model with limited amount of data with which to validate. Kerley's method validates each component in the model to the furthest extent possible, and also uses the model under known conditions to verify that the model correctly predicts the results for those simple cases. This work will draw upon each of these methods, using robust design and tuning along with more traditional V&V to validate the mirror model.

Modeling, simulation, and optimization represent a significant challenge in this thesis. There has been substantial work done in the realms of MDO, model reduction, and validation. These existing techniques will be used to the extent possible, and modified and built upon such that they are appropriate for the mirror system. There is a gap in the literature in using parametric, integrated modeling and optimization for lightweight mirror systems. This thesis will fill this gap and extend these methods for use in technology development for precision-controlled opto-mechanical systems.

3.3 Controlled Structures

A third major area of research from which this work will draw is controlled structures. According to Crawley, Campbell, and Hall [22], a controlled structure is: "one in which there are actuators, sensors and a feedback or feedforward architecture to allow the control of static shape or flexible dynamic behavior." Controlled structures introduce complications in design, which result in significantly improved performance when the structural and control systems are designed together. Crawley, Masters, and Hyde [23] present a methodology for conceptual design and reiterate the importance of considering the controlled structure early in the process.

The Middeck Active Controls Experiment (MACE) was a space shuttle flight experiment that flew in 1995 to investigate approaches to controls-structures interactions (CSI) in a 0-g environment. Research associated with MACE included FEM and measurement based modeling (Glaese [36]), system identification (Jacques [50] and Liu et al [66]), robust controls (How [45, 46] and Grocott [77]) and uncertainty analysis (Campbell [18, 19]), among others.

Many of the achievements of MACE, as well as lists of the many published works can be found in *The Mace Summary Report* [76]. The MACE program produced a great deal of work on modeling of systems and robust control techniques to work with uncertain systems that will be built upon in this thesis. Additionally, robust control theory and applications are summarized in Zhou and Doyle [107], and Grocott [40] presents a number of robust control techniques for use in structural control of uncertain systems. Furthermore, Miller and Grocott [77] discuss why a controlled-structures approach is necessary for high bandwidth control of a flexible adaptive secondary mirror. The methods presented in this set of literature will be used and adapted to the mirror structural control problem.

There has also been significant work done on shape control of various systems, where shape control refers to a system where the control is being used to attempt to achieve a certain shape, for example focusing a mirror. Irschik [49] presents an overview of static and dynamic shape control, mostly through the use of piezoelectric actuation. Shape control has been looked at from simple structures such as beams [5], to two-dimensional plates [83], to more complex structures [94]. The shape control work is primarily focused on actuator type and placement and analytical models for shape control. This will be used and expanded in this thesis to include mirror shape control, while accounting for design constraints.

Controlled structures can either be altered dynamically or quasi-statically. Dynamic controlled structures generally require robust control techniques to account for modeling uncertainties. Quasi-static control is simpler and usually relies upon measured influence functions. In both cases, there is previous literature available from which to draw. These methods will be expanded in this thesis for lightweight mirror control.

3.4 Launch Loads

The final major category of literature applicable to this thesis is launch. The harsh launch environment is the subject of a a great deal of work, including analysis of systems in the launch environment and launch load alleviation techniques. Kabe [57] discusses the launch load analysis process and lessons learned from past systems, focusing on model validation and the types of loading encountered. However, Kabe approaches the launch load analysis as either doing a very simple analysis in preliminary design, or through a very detailed coupled loads analysis with the spacecraft and launch vehicle on the final design. The simple loads analysis is done with a Mass Acceleration Curve (MAC), as described in Trubert [95]. Neither the MAC, nor coupled loads analyses are conducive to conceptual design of a lightweight mirror system where controls will be involved. The MAC is too simplistic for a design where launch survival is of significant concern, and the coupled loads analysis is too time consuming, based on iterative analysis of detailed models, to be used for conceptual design. Also, neither method allows for the addition of control systems directly to the model. These shortfalls motivate the development of a dynamic, state-space launch load analysis technique.

In addition to launch load analysis, there has also been work down on launch load alleviation. Bicos, Johnson, and Davis [14] discuss the need for and benefits from whole-spacecraft vibration isolation. They contend that isolation can reduce weight and cost as well an increase reliability. CSA Engineering has commercially developed isolation systems, known collectively as "SoftRide" [30], which can reduce axial and lateral vibration and shock. Acoustic control has also been investigated. Leo and Anderson [64] have modeled payload fairings to investigate the benefits of proof-mass actuator and piezoelectric acoustic control of the launch vehicle fairing. Similarly, Griffin et al [39] have also examined using proof mass actuators for active acoustic control of the fairing. Furthermore, Glaese [37] and Asari [8] discuss the use of active structural-acoustic control with Sensitivity Weighted Linear Quadratic Gaussian (SWLQG) and impedance matching robust control methods on the launch vehicle fairings to reduce the vibroacoustic loading. Though isolation and fairing control have been considered and analyzed, the literature lacks an assessment of the use of embedded actuators in the payload for launch load alleviation. This thesis will help to fill in this gap.

Additionally, shunted piezoelectrics are potentially of use as a form of passive damping during launch. Hagood and von Flotow [43] present the theory and modeling of piezoelectric materials used in a shunting circuit, and relate the results to mechanical vibration absorbers. Moheimani [79] presents a review of the research on vibration damping with shunted piezoelectrics in the decade following Hagood's work. This work can be built upon and adapted to piezoelectric damping of the mirror using embedded actuators.

The launch environment has been studied because of its harshness. Work has been done characterizing the environment and determining the loads and stresses that a system will see. Preliminary work has also been done on isolation and active acoustic control. Also, while it has not yet been applied to launch, there has been work using shunted piezoelectrics as vibration absorbers. These concepts will be built upon to expand the possibilities for launch load modeling and alleviation techniques for actuated mirrors.

3.5 Literature Summary

The previous four categories: telescopes and mirrors, modeling and optimization, controlled structures, and launch, encompass the bulk of the literature that is relevant to this work. This thesis will draw upon pieces of each of these areas to combine them into an integrated mirror design formulation. While each of the fields, on their own, contains a great deal of work (beyond what is discussed here), there are a few aspects lacking.

- **Lightweight, actuated, SiC mirror trade space analysis.** Significant work has been done in determining material properties and manufacturing techniques for lightweight mirrors, but there is no literature available on the effects of the structural and control system design on the mirror performance. Specifically, the effects of geometric design variables, such as rib structure, is lacking.

- **Design optimization of a high-precision space system early in the design process.** MDO during conceptual design has been used in other industries and on very simple space system models. However, the process has not been applied to precision controlled space systems, such as lightweight mirrors, especially during technology development.

- **Lightweight mirror launch analysis.** There is no existing literature on the effects of launch loads on lightweight mirrors, or the constraints that launch load survivability requirements may impose on the design.

- **Launch analysis methodology for use with optimization, isolation, and control systems.** Launch analysis is typically done with a simple load factors or a very complex analysis. An approach to launch load analysis which provides sufficient detail to use in design and alleviation analysis, while still being general enough to use during the conceptual design, is wanting.

- **Launch load alleviation using embedded actuators.** Launch load alleviation has been examined using isolation or payload fairing control. Conversely, the possibility of using the existing, embedded actuators for passive or active damping during launch has not been studied.

- **Lightweight mirror optimization considering operations and launch constraints.** A design optimization of lightweight mirrors to meet operational performance requirements and launch survival constraints has not been performed.

The work proposed herein will fill in these gaps, and combine and expand upon the aforementioned literature to advance the state-of-the-art in lightweight mirror design and the design process for technology development programs.

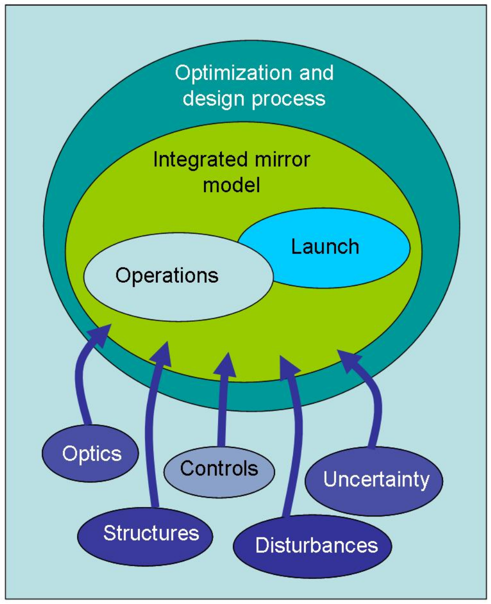

Figure 1: Summary of layered thesis approach

4 Approach

The overall approach for the thesis can be summarized visually in Figure 1. This figure depicts the various aspects involved in the design, and how they fit together. First, there are a number of fields (structures, optics, controls, disturbances, and uncertainty) that feed into an integrated model. Additionally, this integrated model contains the launch and operational performance models. Wrapped around this model is the optimization and design process methodology for the mirror, which could be applied to other similar technology development projects.

Figure 2 depicts the approach for the mirror design chronologically. The initial work is in the development of the mirror model. Once the model is validated, then the disturbance/environment and control system models are added. In the case of launch, the design is taken further to explore alleviation techniques. All of these components are brought together to form the full, integrated modeling tool. Then, model reduction takes place, followed by trade space exploration and optimization, resulting in mirror design guidelines. The design methodology development takes place concurrently, capturing the major aspects of the design process.

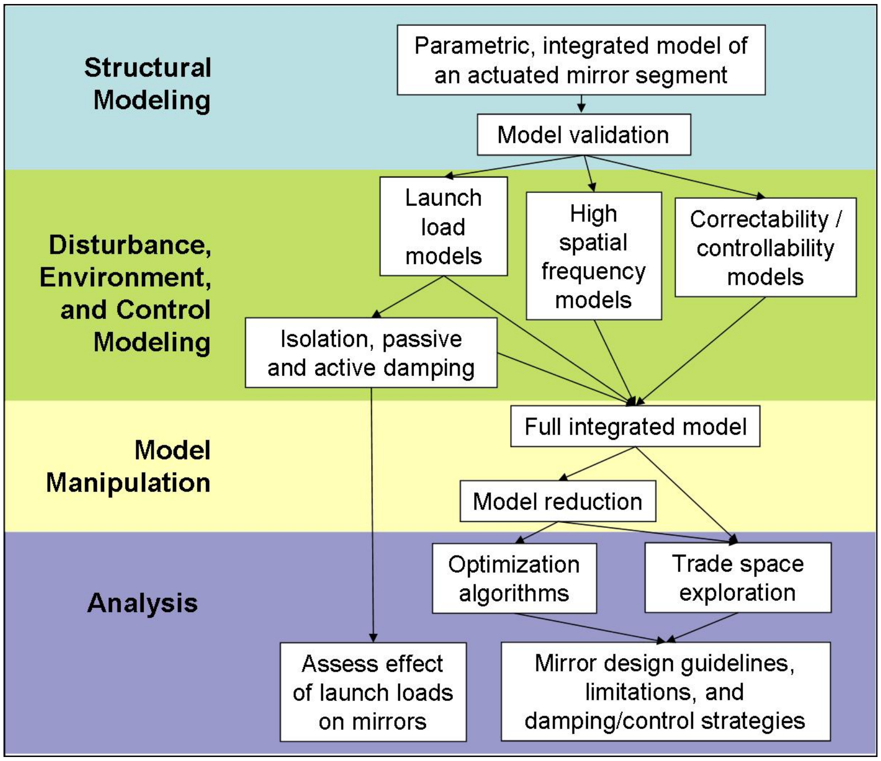

Figure 2: Summary of chronological approach

4.1 Approach Overview

The objectives of this thesis, as stated in Section 2, involve creating an integrated modeling tool, identifying design limitations for SiC mirrors, optimizing the mirror design across launch, controllability, and high spatial frequency error, and developing an integrated modeling design methodology. The approach described herein supports achieving these objectives. Section 4.2 describes the steps through which the integrated model is created. Integrated modeling is a key aspect of this work, and directly supports the first objective. Sections 4.3 and 4.4 describe the launch and operational environment models respectively. These are also a part of the overall integrated model, in support of the first objective. Furthermore, Section 4.3 describes steps involved in implementing various launch load alleviation techniques and exploring the design space of mirrors specifically with respect to the constraints imposed by the launch environment, and Section 4.4 describes the modeling process for the operational performance that will be used to determine optical performance limitations, both in support of the second objective. Section 4.5 describes how to use the model to efficiently analyze and optimize the design space of the entire integrated model. The trade space exploration and optimization supports the third objective. These steps combine to create the design methodology, as described in Section 4.6, in support of the final objective.

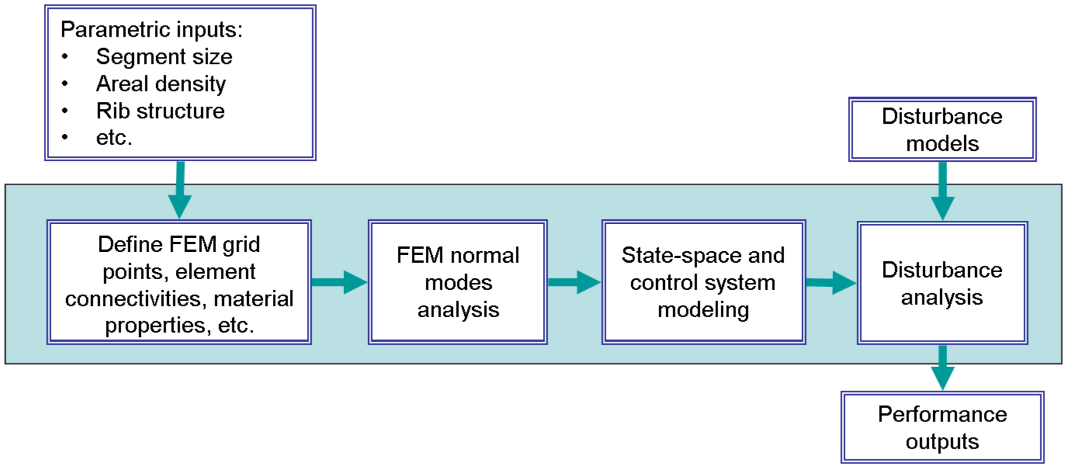

Figure 3: Integrated mirror modeling overview

The forthcoming sections detail an approach to accomplish the objectives identified, and to advance the state-of-the-art in lightweight mirror design.

4.2 Integrated Model

A key aspect of the thesis is the integrated mirror model. Parametric, integrated modeling has many benefits, including an ability to create and analyze different designs over multiple disciplines, as described in Uebelhart [99] and others. By keeping all relevant design parameters (geometry, structural, control, etc.) in a single input file and auto-generating models and analyses, the design space can be explored and optimization is possible. The integrated mirror model that is considered here contains a number of component models, including finite element models, state-space models, control systems, and disturbance models, along with disturbance analysis, to calculate performance outputs given a set of parametric inputs. A block-diagram of the integrated modeling process is shown in Figure 3.

4.2.1 Mirror Model

The mirror model is created using finite element modeling (FEM) and state-space modeling techniques. The structural model is made with FEM, and can be seen in Figure 4. The model is of a single mirror segment that is rib-stiffened with silicon carbide material properties. There are surface-parallel electrostrictive actuators embedded in the ribs, allowing for actuation of the mirror, which are shown as red bars in Figure 4. The actuators expand or contract with an applied voltage, producing a moment on and changing the shape of the mirror surface. The geometric properties of the mirror, such as curvature, areal density,

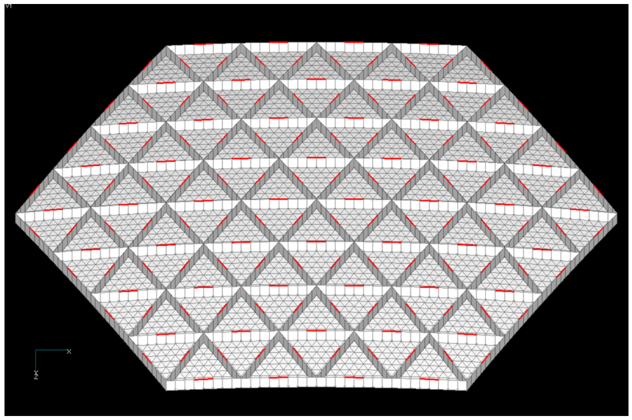

Figure 4: Mirror finite element model with actuators, showing the back (non-reflective) surface

number of ribs, rib aspect ratio, and percent of mass in the face sheet, are all parameters that can be varied. The grid points, elements, and material properties are all defined automatically based on the input parameters within Matlab, and the resulting normal modes solution is solved using Nastran. Specifically, Nastran is used to solve for the frequencies and mode shapes of the system. These results are brought back into Matlab where they are manipulated into a state space model.

The frequencies (Ω) are used to define the dynamics of the system, or the A matrix in the state-space model. The mode shapes (Φ) are used in combination with the desired input and output grid points and types to determine the full state-space model, which is shown in Equation 1.

$$\begin{aligned}\begin{bmatrix}\dot{q}\\ \ddot{q}\end{bmatrix} &= \begin{bmatrix}0 & I\\ -\Omega^2 & -2\zeta\Omega\end{bmatrix}\begin{bmatrix}q\\ \dot{q}\end{bmatrix} + B_w w + B_u u\\ y &= C_y\begin{bmatrix}q\\ \dot{q}\end{bmatrix} + v\\ z &= C_z\begin{bmatrix}q\\ \dot{q}\end{bmatrix} + D_{zu}u\end{aligned} \tag{1}$$

Here, q are the modal degrees of freedom, Ω are the modal frequencies, ζ is the prescribed modal damping, w is the disturbance input, B_w defines how the disturbances are input into the system, u are the control commands, B_u defines how the actuator commands are input to the system, y are the sensor outputs, C_y relates the sensor outputs to the states, v is sensor noise, z are the performance outputs, C_z relates the performance outputs to the states, and

D_{zu} relates the performance outputs to the control inputs.

The inputs and outputs of the model are defined based on the desired disturbances, performance outputs, and control systems. For example, in the launch analysis, the desired outputs are stresses in the elements. The nodal displacements, which are readily available using the FEM and mode shapes, are transformed using the C_z matrix such that the outputs become stresses in the elements. Similarly, the B_w matrix is defined to accept the vibrational accelerations at the base of the mirror and the acoustic pressure on the mirror surface, and the B_u matrix relates the model to the piezoelectric inputs. In this manner, the entire state-space mirror model is built. More details can be found in Cohan and Miller [21].

4.2.2 Control Systems

The control systems will relate the sensor outputs (y) to the actuator inputs (u). It is likely that a number of different control laws will be used for (1) the different disturbance environments (operational versus launch), and (2) comparison of performance of different types of control systems. The various types of control used for the different environments are discussed in those particular sections (Sections 4.3 and 4.4).

4.2.3 Disturbance Models

The disturbance models will describe the environments in which the mirror must operate. The two major environments considered here are launch and on-orbit operations, described in Sections 4.3 and 4.4 respectively. One key aspect of the disturbance modeling is that the set-up of the integrated model allows one to easily add more disturbances, or change the disturbance as more information comes available. For example, the vibration and acoustic power spectral density (PSD) functions are parameterized, and can easily be changed to mimic alternate launch vehicles. Furthermore, the parameterization of the modeling codes allows easy addition of yet unknown or unconsidered disturbances in the future, so that the model adapts to increasing amounts of information.

4.2.4 Model Validation

As with any model, it is extremely important to validate the model before it is used to draw any conclusions. Model validation will be done to the furthest extent possible. There is limited test data to compare to, but there are a few data points where the model can be compared to physical test data. Thus far, the model has been compared to test data for:

- Fundamental frequency

- High spatial frequency residual error from a prescribed focus change
- Vibration induced stress (for silicon carbide and actuators)

In all cases, the model agrees with the test data within 10%. Additionally, the acoustically induced stress has been compared with analysis results from a large acoustic analysis done elsewhere. The model agrees with this data within 20%, though there are more variables in the acoustic stress application, such as the number of patches as described in Section 4.3.1, that could account for this difference. As additional test data and more data points become available, the model will be continually tested, and updated if necessary.

In addition to model-data calibration, the model is also validated by using simple scenarios with known, analytical results. For example, the stress calculations, relating the mode shapes to elemental stresses, have been computed for a cantilever beam. The resulting stresses using the modeling method of this thesis agree with the analytical results for stress in a cantilever beam, validating that particular calculation and the level of fidelity in the model.

Overall, model validation on this problem is difficult, but can be done by validating the individual pieces of the model to the furthest extent possible, and by using any test data that is available. A benefit of the parametric model is that it allows the model to be calibrated against different test set-ups by easily changing the model parameters to mimic that particular test article.

In summary, the integrated model is set up such that it is conducive to adding multiple disturbance environments and control systems, and to doing trade space exploration by changing design parameters. The mirror model has been described, and the launch and operational environments and modeling are described in the following sections.

4.3 Launch Load Analysis and Alleviation

As mentioned previously, launch survivability has been identified as a major issue in lightweight mirror design. Therefore, one goal of this thesis is to identify limitations on design variables for launch survival, and to examine launch load alleviation techniques to expand the space of feasible designs, where feasible designs are those that will survive the launch.

4.3.1 Methodology

The launch load alleviation task will be undertaken through the use of a dynamic, state-space model, as identified above (Equation 1). This method is a deviation from traditional launch load modeling [57], but it offers a number of benefits. Mainly, with the dynamic

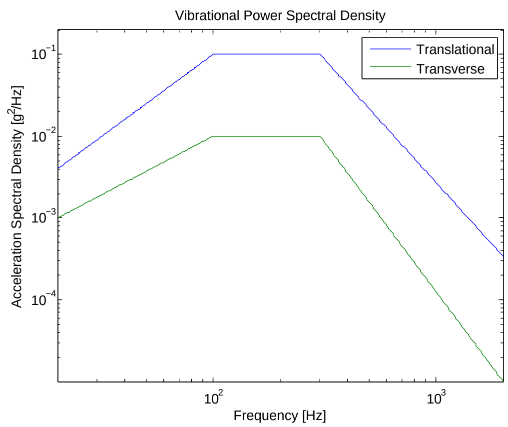

Figure 5: Vibration acceleration spectral density

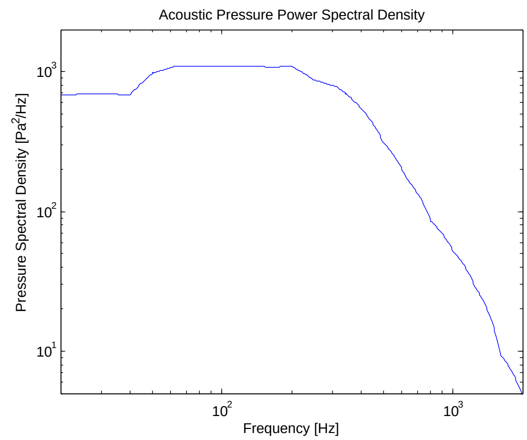

Figure 6: Acoustic pressure spectral density

model formulation, all isolation, control systems, etc. can be added directly into the model in Matlab using state-space techniques. In addition to the simplification of having a single model, this formulation also allows the same FEM to be used for a number of different analyses, realizing a computational cost savings. Furthermore, typical Nastran-only launch load analyses do not facilitate active control, thus this methodology provides an environment in which it is possible to investigate active control with embedded actuators.

The vibrational and acoustic disturbances are the inputs to the model associated with the launch problem. These are input in terms of acceleration spectral densities and pressure spectral densities respectively. Vibration and acoustic pressure levels can be found for various launch vehicles. The vibration is described in terms of an acceleration spectral density (pictured in Figure 5), which can be applied to the state space model as a random analysis with a steady-state frequency domain disturbance analysis. Similarly, acoustic levels are specified in terms of sound pressure levels (SPL) as a function of frequency. The SPL can be converted to a pressure spectral density (Figure 6), which can similarly be used in a disturbance analysis and applied to the surface of the mirror.

To apply the acceleration spectral density, rather than a traditional power spectral density in which force is applied, the "big M" method is used [82, 90]. Here, a large, concentrated mass is used on a base structure, and a PSD scaled by the square of the magnitude of the large mass is applied as a typical force PSD, so that the system experiences the desired accelerations.

The acoustic pressure is induced by applying a force to every node on the mirror surface, and scaling the pressure spectral density by the square of the area associated with each node. One caveat in the application of the acoustic pressure is the area over which the pressure waves are correlated. The "patch method" of correlation will be used, where the acoustic pressure is correlated over patches of the mirror surface, and the number of patches depends on the frequency [88].

The primary performance output is stress. The elemental stresses must be below the yield stress of silicon carbide through factors and margins of safety. The stresses are automatically computed from nodal displacements through interpolation functions [12, 21]. The performance outputs resulting from the disturbance inputs are computed using a frequency-domain disturbance analysis as follows. The integrated state-space model of the closed loop system is transformed into a frequency domain transfer function matrix:

$$G_{zw} = C_z(sI - A)^{-1}B_w \tag{2}$$

The PSD of the output can then be found using:

$$S_{zz} = G_{zw} \cdot S_{ww} \cdot G_{zw}^H \tag{3}$$

where S_{zz} is the PSD of the output, S_{ww} is the PSD of the disturbance input (Figures 5 and 6), G_{zw} is the system transfer function matrix, and ^{H} is the hermitian operator. The mean squared value of the outputs can then be found:

$$\bar{z}_i^2 = \frac{1}{2\pi}\int_{-\infty}^{+\infty} S_{zz}(j\omega)_{i,i}d\omega = \frac{1}{\pi}\int_{0}^{+\infty} S_{zz}(j\omega)_{i,i}d\omega \tag{4}$$

The square root of $\bar{z}_i^2$ yields the root-mean-square value of the resulting stress output.

4.3.2 Alleviation Techniques

As mentioned previously, a number of alleviation techniques will be analyzed: isolation, passive damping, shunted piezos, and active damping. The first, and simplest, is the use of isolation. Isolation can reduce the amount of vibrational disturbance the mirror receives from the rest of the structure. Isolation will be implemented as a state-space system and added to the mirror model. Another alleviation technique is shunted piezos, where the embedded actuators are used to passively damp the system. Instead of the usual use where a voltage is applied and the actuators force the system, the actuators will instead be used in reverse to absorb the energy from the system. The final alleviation technique is active damping, where the embedded actuators are used to actively damp the motion of the mirror to reduce the stresses. This is the most complex method, and will be implemented as a robust state-space controller relating the sensor outputs to the embedded actuator inputs. The sensor for the launch problem has not yet been finalized, but a likely option is to use a set of strain gauges. The model is inherently uncertain, and will never perfectly resemble the true system. Therefore, any model-based control must be implemented with robust or desensitized control methods, or it will not work on the system. Additionally, it would be naive to believe that a general controller could be used for a system without specifically tailoring the gains and parameters for that particular system. Therefore, the controlled performance will be used to gain an understanding of the potential improvements resulting from the use of active control, and for comparing across different mirror designs to determine which designs perform best with active control. Furthermore, the effects of uncertainty on the control performance will be investigated to determine the accuracy with which the model must be known in order to realize performance improvements. These insights will be used to determine the extent to which active damping should or should not be pursued in the future.

4.3.3 Launch Design Space

The launch design space will be explored both with and without the launch load alleviation techniques. The simplest way to achieve survivability is to have a mirror that will survive without the aid of any alleviation techniques. Therefore, the first step in the launch design space is to map out the trade space of design variables to determine limitations on the technology. This will be done through trade space exploration. Then, the various alleviation techniques described above will be added one at a time to determine how the feasible design space changes. Additionally, uncertainty will be added to the system to determine its effects and determine the robustness of the alleviation techniques.

4.4 Operational Performance Modeling

The primary objective of the mirror is to meet imaging quality requirements. Therefore, the optical quality of the mirror during operations is a critical piece of mirror design. The two aspects of operations that will be considered are correctability, in terms of the range of shapes to which the mirror can be controlled, and the residual high spatial frequency error.

This model will build upon previous work by Gray [38] and Jordan [53]. The operations disturbance model will be implemented as a commanded shape change and thermal disturbance. The complex structure and the coefficient of thermal expansion (CTE) mismatch between the actuators and the silicon carbide substrate result in a deformation of the mirror due to a bulk temperature change. Therefore, one way to apply a disturbance is to apply a temperature change to the mirror and calculate the correctability. The second form of disturbance is through a commanded shape change. A commanded change causes the disturbance that results in high spatial frequency error, as seen in Figure 7. This will be done through

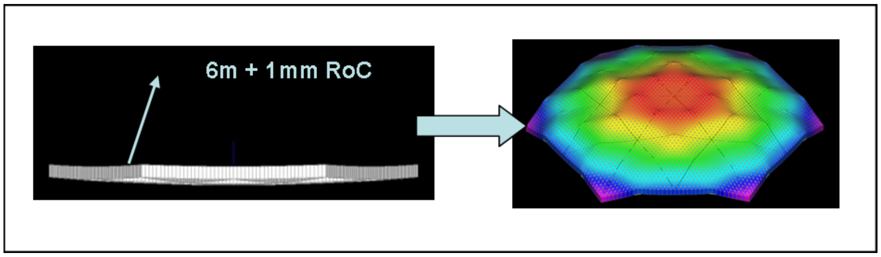

Figure 7: High spatial frequency disturbance induced through a commanded low frequency shape

the use of influence functions and control actuation. The performance metric outputs will be twofold. The first metric is the residual wavefront error due to uncorrectable, high spatial frequency error from induced actuation, computed in terms of zernike coefficients [106]. The second metric is the range of correctability, or how big of a commanded shape change can be achieved with the embedded actuators with limited stroke.

During the operational, imaging performance phase, the control will likely be quasi-static. As stated above, the primary control functions envisioned are (1) to control the shape of the mirror to some desired shape, and (2) minimize the amount of residual high-spatial frequency error due to controlling a desired shape. Reasons to change the shape of the mirror include: changing the optical prescription, rejecting thermal disturbances, counteracting manufacturing imperfections, and phasing multiple mirror segments. All of these changes occur very slowly, and can lead to a "set and forget" or quasi-static control scheme where, compared to the dynamics of the system, the control bandwidth is slow, and the dynamics can be ignored. For example, the sensor would detect a discrepancy in the mirror shape, the control system would calculate the necessary actuator inputs to correct the shape, and the commands would be sent to the mirror. Well after the vibrations had settled, at a later period of time (minutes), the process could repeat. The actual bandwidth is TBD, but the time scale differences between the dynamics and the control allow for quasi-static control, which is significantly less complex than full dynamic control. This has a number of benefits. First, it decreases the complexity of the system and the supporting electronics. Second, the control can be performed with influence functions, which can be measured on the actual system, reducing the dependence of the control system on the model, and improving robustness, making the results more widely applicable.

4.5 Optimization and Trade Space Exploration

The integrated model, including the disturbance and control models, will be assembled in Matlab, where the optimization and trade space exploration will also take place. To begin, initial trade space exploration will occur to gain a preliminary picture of the design space. Then, the optimization can take place to search for families of designs that are promising in terms of their prospect for overall performance.

4.5.1 Model Reduction

A component of the optimization will be model reduction. The initial model must be high-fidelity. However, high fidelity models are not conducive to optimization as they are too computationally expensive to run repeatedly. Therefore, a model reduction technique will be employed to speed up the optimization while preserving accurate results. Once the model is complete, a thorough analysis of the model and various reduction techniques will be undertaken to determine which, if any, reduction techniques will work well with this particular problem. Additionally, numerical conditioning will be checked to ensure accurate results, and to avoid ill-conditioning resulting from the model reduction.

There are a few reduction techniques that are promising, but judgment on their usage is reserved until the model is complete and the results from the reduced model can be compared with those from the original model. One such technique involves exploiting the circulant symmetry of the system. Through a number of transformations, a circulant system can be made block diagonal and reduced significantly [41]. Other techniques include balanced truncations, where only those states with significant controllability and observability energy are kept in the system and the states with less are truncated [98, 104], or a combination of circulance and balanced reduction. Less formal techniques include being able to calculate stresses at key locations around the mirror, rather than at every element. For example, the vibration-induced stresses are always highest near the mounts, making those the most significant elements for stress calculations. Furthermore, by initially using the appropriate model fidelity, as described in Howell [47], the size of the FEM can be limited such that there are not more elements and grid points than necessary. Through the use of model reduction or approximation methods, a model of reasonable size and speed will be created for use with an optimization routine.

4.5.2 Optimization Algorithms

The optimization will take place using a hybrid technique. The mirror inherently has both continuous and discrete design variables. Discrete variables include the number of actuators and the number of ribs, while continuous variables include the areal density, curvature, and thicknesses. In general, gradient based optimization techniques are not conducive to discrete variables, but are quite good with continuous variables. On the other hand, heuristic optimization techniques are very computationally expensive and are not guaranteed to find the optima. Therefore, a hybrid technique will be used in order to take advantage of the benefits of both, while limiting their adverse effects.

Additionally, the optimization will be formulated such that the sensitivities to uncertainty in the performance or design variables are low. Local optima that are surrounded by areas of poor performance are not useful for the technology development proposed herein. Rather, areas where there are a lot of good designs with similar performance will be sought. The true "optimum" is of less importance because of the uncertainty in the model. This means that the convergence tolerances can be relatively large, and that finding a number of local optima, rather than a single, global optimum, is useful.

4.5.3 Objective Functions

There are a number of objectives which pertain the the mirror performance in each of the various environments that have been discussed. Each of those objectives are important, and need to be considered in the optimization. A number of objective functions will be utilized to explore the design space, and find the families of designs that perform best under certain conditions. For example, objectives will include:

- Best operational performance while meeting launch survival constraints
- Meets minimum operational performance requirements and launch survival constraints with least amount of actuators and control
- Most lightweight system meeting all requirements
- Best combination of launch and operational performance
- Highest fundamental frequency for a fixed areal density

As the model and research progresses, the objective functions will be added to and modified. Also, the initial trade space exploration will help to identify areas where trade-offs need to be made, and will suggest additional objective functions. The goal is to have a set of objective functions, that, when combined, will identify families of designs that have strong potential to provide good mirror performance, and should be investigated further.

4.6 Design Methodology using Integrated Modeling

Technology maturation is a difficult task. Because is often expensive, and success is not guaranteed, the technology development process deserves a great deal of attention. This thesis will use integrated modeling as a method of guiding the technology development process. The approach will be to use the model as a source of corporate knowledge about the technology, incorporating test data, insights, and lessons learned into the model. Any results from tests or prototypes will be used to not only validate the model, but also to identify areas where work is needed, and to guide the model to include those areas. For example, a test indicated that the desired shape change of the mirror may induce high spatial frequency wavefront error. With this result, a capability for modeling high spatial frequency residual error was added to the model to capture that effect. Furthermore, optimization can be used to guide the design by determining families of designs that have good performance, and identifying necessary tests or prototypes to advance the technology further. This results in an iterative process of testing, analyzing, and optimizing the design, with the model at the center of the process. This methodology will be developed concurrently with much of the modeling, as the evolution of the integrated mirror model represents the core of the process.

4.7 Approach Summary

The overall approach to the thesis is largely based on integrated modeling. The model consists of FEM, state-space, disturbances, and controls. Once the model is formulated and validated, a trade space exploration will follow. There will be trade space exploration done for the overall mirror design, and also for the launch survivability guidelines. The launch trade space will lead to technology limitations and guidelines for launch survival, and the overall mirror design space will help to define the optimization objectives. The model will be reduced appropriately, and then used with optimization algorithms to identify the design trends that show the most promise, leading to advancement of lightweight mirror design, as well as a methodology for determining steps in technology maturation programs.

5 Contributions

Potential contributions of this thesis include:

- Guidelines for the design of lightweight actuated mirrors, specifically considering peak launch stress, correctability, residual wavefront error, and mass, including both structural and control system design
- Identification of designs and design parameters that contribute to the performance of the mirror, as specified above, including those that are robust to uncertainty

- Characterization of the limitations on lightweight, silicon carbide mirrors for launch survival
- Analysis and feasibility of launch load alleviation techniques, including shunted piezos and active damping with embedded actuators
- Identification of the limitations on mirror design with respect to correctability and wavefront error
- Integrated modeling framework to support technology maturation
- Methodology for capturing developmental experience in a model over its life cycle
- Model reduction of a high-fidelity model for optimization and control

6 Thesis Outline

This section introduces a preliminary thesis outline.

1. Introduction
   (a) Problem description
   (b) Motivation
   (c) Literature review
2. Integrated modeling methodology and design process
   (a) Parametric, integrated modeling philosophy for precision, opto-mechanical systems
   (b) Benefits, challenges, and applicability to other systems
3. Model details
   (a) Finite element model and state-space mirror models
   (b) Disturbance models
   (c) Control algorithms and implementation
4. Model usage
   (a) Model reduction
   (b) Optimization
5. Results and analysis
   (a) Mirror design families with the best performances

(b) Limitations on technologies and design variables

6. Conclusions

   (a) Lessons learned
   (b) Extension to other systems
   (c) Contributions

7 Proposed Schedule

The following schedule is proposed for this work.

Milestones:

- Complete:
  - *Qualifying Exams: January 2007*
  - *Masters Thesis: June 2007*
  - *Admission to Doctoral Program: June 2007*
  - *Thesis Committee Formed: April 2008*
  - *Course Requirements Complete: May 2008*
  - *Minor Approved: October 2008*
- Thesis Proposal and Proposal Defense: December 2008
- Thesis Approval and Defense: Spring 2010

The following research schedule supports the milestones listed above.

- Fall 2007 - Spring 2008
  - Develop thesis topic
  - Literature review
  - Develop integrated mirror model
  - Identify launch load disturbance models
- Summer 2008
  - NRO Internship
  - Literature review
  - Validate model
- Fall 2008

  - Design methodology development
  - Finalize and validate mirror model and launch load models
  - Determine mirror limitations for launch survival
  - Begin passive and active damping

- Spring - Summer 2009
  - Finish passive and active damping
  - Combine/build models across disturbance environments
  - Model reduction

- Fall 2009
  - Analysis and optimization of system including launch loads, operations, and complexity
  - Conclusions and guidelines for mirror design

- Spring 2010
  - Finalize, write, and defend thesis

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