Integrated Modeling for Lightweight, Actuated Mirror Design

Lucy Cohan
Thesis Proposal Defense
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Introductions

• Thesis Committee:
  – Professor David W. Miller (Committee Chair)
  – Professor Karen Willcox
  – Dr. Howard MacEwen
  – Professor Jonathan How (Minor Advisor)

• External Examiner:
  – Professor Olivier de Weck

• Department Representative:
  – Professor Jaime Peraire
Outline

• Motivation
• Problem statement and objectives
• Literature review
• Approach
  – Integrated modeling
  – Launch load analysis and alleviation
  – Operational performance
  – Optimization and trade space exploration
  – Methodology for technology maturation
• Potential contributions
• Preliminary thesis outline
• Schedule
Research Motivation

- Increased resolution and sensitivity in space-based optical systems requires larger reflecting areas.

- Lightweight, actuated mirrors are an enabling technology for larger primary apertures.

- Deviation from traditional telescopes, lack of knowledge on design:
  - Many issues still need to be solved.
How do you design a mirror that will survive launch and perform well on-orbit, in terms of wavefront error and correctability?

**Specific Mirror Issues**

- **Survivability**
  - Arrive on orbit undamaged

- **Operational performance**
  - Low wavefront error (WFE)
  - Mirror is correctable

**Challenges**

- Multiple disturbance types and environments
- Controlled structure
- High precision (optical tolerances)
- Multidisciplinary (structures, optics, controls, etc.)
- High-fidelity models required

Using integrated modeling and multidisciplinary optimization
Scope

Lightweight mirror development for large aperture systems

- Manufacturing
- Sensor (CCD)
- Actuator design
- Telescope and mission design
- Wavefront sensing
- Observation scenarios
- Etc…
Scope

Lightweight mirror development for large aperture systems

Mirror design

- Manufacturing focus error
- Thermal
- Print through
- Dimpling
- Dynamics

Error Sources

- Launch vibe
- Launch acoustic

Observation scenarios

- Wavefront sensing
- Actuator design
- Telescope and mission design
- Manufacturing
- Sensor (CCD)

Etc…
Lightweight mirror development for large aperture systems

**Performance Objectives**

- Low spatial frequency correctability
- Manufacturing focus error
- Thermal
- Launch vibe
- Launch acoustic
- Dimpling
- Print through

**Mirror design**

- Telescope and mission design
- Wavefront sensing
- Observation scenarios
- Actuator design
- Manufacturing
- Sensor (CCD)

**Etc…**
Objectives

• 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 mirrors and mirror control systems

  2. Characterize the *limitations* of lightweight, actuated, SiC mirrors
     • Low spatial frequency correctability limit
     • High spatial frequency wavefront error
     • Launch survival

  3. Identify *favorable mirror architectures* through trade space exploration and optimization
     • Performance metrics: peak launch stress, high spatial frequency error, correctability, mass, and actuator channel count

  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*
Literature Review - Overview

Disciplines
- Optics
- Controls
- Structures
- Optimization
- Disturbances
- Systems
- Uncertainty
- Dynamics

Relevant Areas of Literature:

**Telescopes and Mirrors**
- Space and ground telescope modeling
- Lightweight mirror development
- Active optics

**Modeling and Optimization**
- Parametric, integrated modeling
- Multidisciplinary optimization
- Model reduction
- Model validation

**Controlled Structures**
- MACE
- Robust Controls
- Shape control

**Launch**
- Environment
- Analysis
- Alleviation
Literature Review – Telescopes & Mirrors

• **Space telescopes** (Stahl, Peterson, Lillie, Bronowicki, MacEwen)
  - Trends – increasing amount of actuation (isolation, mirror, whole spacecraft)
  - Integrated modeling efforts
  - JWST – ongoing development, will be state-of-the-art in space-telescope when it launches (2013)

• **Ground telescopes** (Angeli, MacMynowski)
  - GSMT program – fundamentally different disturbances, but still complex and modeling techniques are useful

• **Lightweight mirrors** (Matson, Burge, Stahl, Angel, Ealey, Kowbel))
  - AMSD – investigate multiple mirror materials
  - Silicon Carbide – benefits for low areal density systems, manufacturing, etc.

• **Active optics** (Tyson, Ealey, Angeli, Hardy)
  - Deformable mirrors (ground telescopes)
  - Shape control – largely quasi-static
Literature Review – Modeling and Optimization

- **Integrated modeling** (MOST, Angeli, Blaurock, Uebelhart, Genberg)
  - Parametric, integrated modeling
  - Modeling environments
  - Point design integrated models

- **Multidisciplinary optimization** (Sobieski, Haftka, de Weck, Jilla)
  - Algorithms (gradient based, heuristic)
  - Challenges – reduction, modeling, sensitivity

- **Model reduction and approximations** (Moore, Grocott, Willcox, Haftka, Robinson)
  - Reduction techniques – balancing, etc.
  - Approximation methods
  - Symmetry – circulance

- **Validation and verification** (Balci, Babuska, Masterson, MACE)
  - Model-data correlation
  - Tuning and robust designs
Literature Review – Controlled Structures

• “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” –Crawley, Campbell, and Hall

• MACE (Middeck Active Control Experiment) (Miller, Crawley, How, Liu, Campbell, Grocott, Glaese, etc.)
  – SERC flight experiment in 1995
    • Modeling (FEM and measurement based)
    • System ID
    • Robust controls
    • Uncertainty analysis

• Robust controls (Zhou & Doyle, Grocott, How)
  – Control techniques that take uncertainty into account
  – Performance guarantees for a given uncertainty model (less uncertainty yields better performance)

• Shape Control (Irschik, Agrawal)
  – Quasi-static
  – Control shape of: beam, plate, complex structure (mirror)

Literature Review – Launch

- **Environments** (Payload planners guides, etc.)
  - Load factors
  - Vibration environments
  - Acoustic sound pressure levels

- **Analysis** (Kabe, Trubert, Sarafin)
  - Coupled loads analysis
  - Mass Acceleration Curve (MAC)

- **Alleviation**
  - Isolation (Bicos, CSA)
    - Whole spacecraft
    - Individual components
  - Launch faring damping (Leo, Anderson, Griffin, Glaese)
    - Acoustic control with proof-mass actuators
  - Shunted Piezoelectrics (Hagood, von Flotow, Moheimani)
    - Piezos to absorb energy
    - Act like mechanical vibration dampers
Objectives

• Explore the trade space of space telescope design through parametric, integrated modeling

• Lightweight, actuated mirror design and control

Relevant Work

• Modeling for dynamic launch loads and launch load alleviation (Cohan)

• Design for minimization of high-spatial frequency error (Gray)

• Effects of actuator length and spacing (Smith)

• Mirror athermalization (Jordan)

• Parametric modeling and uncertainty analysis (Uebelhart)

• Model fidelity (Howell)

• Control architecture for on-orbit vibrations (Cohan)
Approach: Overview

Integrated Mirror Model

Launch Loads

Operational Performance

Fully Integrated Model: Mirror Optimization

Technology Maturation
Approach: Overview

Integrated Mirror Model
- Parametric, integrated model of an actuated mirror segment
- Model validation
- Define figures of merit

Launch Loads

Operational Performance

Fully Integrated Model: Mirror Optimization

Technology Maturation
Approach: Overview

Integrated Mirror Model

Launch Loads
- Nothing, isolation, passive damping, or active damping

Model validation

Launch load model

Design for launch

Operational Performance

Model validation

Low spatial frequency correctability model

Design for correctability

High spatial frequency WFE model

Design for high spatial frequency WFE

Fully Integrated Model: Mirror Optimization

Technology Maturation
Approach: Overview

Integrated Mirror Model

Launch Loads

Fully Integrated Model: Mirror Optimization
- Define optimization objectives
- Optimization and isoperformance
- Model reduction and conditioning
- Trade space exploration
- Mirror design guidelines, limitations, and damping/control strategies

Operational Performance

Technology Maturation
- Technology maturation methodology
Approach: Overview

Integrated Mirror Model
- Parametric, integrated model of an actuated mirror segment
- Model validation
- Define figures of merit
- Completed

Launch Loads
- Model validation
- Launch load model
- Design for launch
- Nothing, isolation, passive damping, or active damping

Fully Integrated Model: Mirror Optimization
- Define optimization objectives
- Optimization and isoperformance
- Model reduction and conditioning
- Trade space exploration
- Mirror design guidelines, limitations, and damping/control strategies

Operational Performance
- Model validation
- Low spatial frequency correctability model
- Design for correctability
- Design for high spatial frequency WFE
- High spatial frequency WFE model

Technology Maturation
- Technology maturation methodology

Approach: Integrated Model Development

Parametric inputs:
- Segment size
- Areal density
- Rib structure
- etc.

Define FEM grid points, element connectivities, material properties, etc.

FEM normal modes analysis

State-space modeling

Disturbance analysis

Disturbance models

Performance outputs

High Spatial Frequency Dimpling Error

Stress Distribution (MPa)

6m + 1mm RoC
Approach: Launch Loads

- Normal modes analysis
- Interpolation functions
- Model manipulation
- Disturbance analysis

- Dynamic formulation (state-space)
- Launch load alleviation:
  - Isolation
  - Passive damping using embedded actuators as shunted piezoelectrics
  - Active damping with embedded actuators and robust control methods
Approach: Operational Performance

- Command low order shapes to correct for thermal or manufacturing, or to change the prescription
  - Limited number of actuators with limited stroke → how big of a shape change is achievable?
- Command low order shape, induce high spatial frequency WFE
  - How do you design the mirror to minimize the residual WFE?

Bulk Temperature Change Applied

Control:
- Quasi static
- Based on influence functions
- Least-squares
Approach: Mirror Optimization

Mirror Model
- Launch stress and alleviation models
- High spatial frequency error models
- Correctability/Controllability

Combine models of various design components
- Launch
- Operational performance

Optimization Algorithms
- Gradient based for continuous variables
- Genetic algorithms for discrete variables

Model Reduction
- Circulence
- Balanced Reduction
- Others

Mirror Guidelines
- Technology limitations
- Promising families of designs
- Areas where more data is needed

Objective Functions
- Separable designs (lowest stress, WFE, etc)
- Lowest mass that meets requirements
- Others to be identified
Approach: Methodology for Technology Maturation

- Model-centric approach to design
- Model captures all lessons learned, data, and corporate knowledge about the technology throughout the design process
- Use model with optimization to:
  - Determine where more data is needed (prototypes or tests)
  - Identify favorable designs (in terms of specified performance metrics)
  - Design operational systems
  - Make launch go/no-go decisions for systems that cannot be fully tested on the ground
- Demonstrate process with lightweight mirror model
Potential Contributions

- **Guidelines** for the design of lightweight actuated mirrors, including both structural and control system design, considering:
  - Peak launch stress
  - Correctability
  - Residual wavefront error
  - Mass
  - Actuator channel count

- Identification of design variables to which the performance is sensitive, as well as identification of designs with performance that is robust to parameter uncertainty

- **Limitations** of lightweight, silicon carbide mirrors for launch survival

- Analysis and feasibility of launch load alleviation techniques, including shunted piezos and active damping with embedded actuators

- **Limitations** on mirror design with respect to correctability and WFE

- Integrated modeling methodology to support technology maturation and to capture developmental experience in a model

- **Model reduction** of a high-fidelity model for optimization and control
1. Introduction, motivation, literature review
2. Integrated modeling methodology and design process
   • Parametric, integrated modeling philosophy for precision, opto-mechanical systems
   • Benefits, challenges, and applicability to other systems
3. Model details
   • FEM and state-space mirror models
   • Disturbance models
   • Control algorithms and implementation
4. Using the model
   • Model reduction
   • Optimization
5. Results and analysis
   • Mirror design families that perform best
   • Limitations on technology, design variables
6. Conclusions, lessons learned, extension to other systems, contributions
Proposed Schedule

Spring/Summer 2007
- Masters thesis (June 07)
- NRO mirror control work

Fall 2007 – Spring 2008
- Develop thesis topic
- Literature review
- Develop model of launch loads
- Thesis committee

Summer 2008
- NRO Internship
- Literature review
- Finalize/validate model

Fall 2008
- Design methodology
- Determine mirror limitations for launch survival
- Passive and active damping
- Prepare and defend thesis proposal

Spring/Summer 2009
- Passive and active damping
- Combine/build models across disturbance environments
- Model Reduction

Fall 2009
- Analysis and optimization of system including launch loads and other disturbance sources
- Conclusions and guidelines for mirror design

Spring 2010
- Finalize, write, and defend thesis
Thank you!

Questions and Discussion
Telescopes and Mirrors

Modeling and Optimization

References (3)

Controlled Structures


Launch