Integrated Modeling for Lightweight, Actuated Mirror Design

Lucy Cohan

Thesis Proposal Defense

8 Dec 2008

Introductions

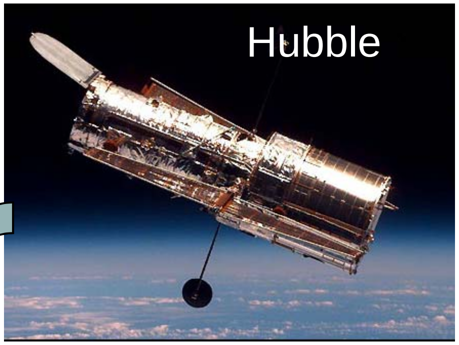
- Thesis Committee:
  - – Professor David W. Miller (Committee Chair)
  - – Professor Karen Willcox
  - – Dr. Howard MacEwen
  - – Professor Jonathan How (Minor Advisor)
- External Examiner:
  - – Professor Olivier de Weck
- Department Representative:
  - – Professor Jaime Peraire

Outline

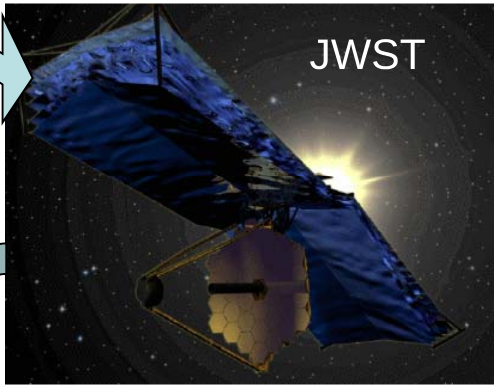
- Motivation
- Problem statement and objectives
- Literature review
- Approach
  - Integrated modeling
  - Launch load analysis and alleviation
  - Operational performance
  - Optimization and trade space exploration
  - Methodology for technology maturation
- Potential contributions
- Preliminary thesis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



2.4 m primary mirror
~180 kg/m^2



6.5 m segmented primary mirror
~30 kg/m^2

Future
10-20 m segmented primary mirror
~5 kg/m^2

Integrated Mirror Design

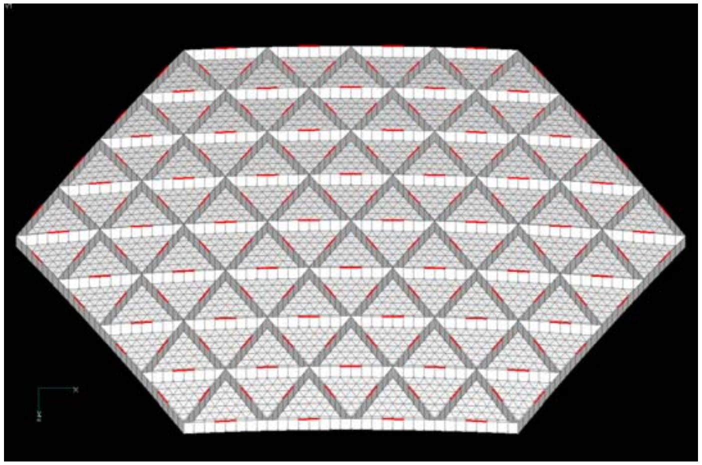
How do you *design* a **mirror** that will *survive launch* and *perform well* on-orbit, in terms of wavefront error and correctability?

Specific Mirror Issues

- **Survivability**
  - Arrive on orbit undamaged
- **Operational performance**
  - Low wavefront error (WFE)
  - Mirror is correctable

Challenges

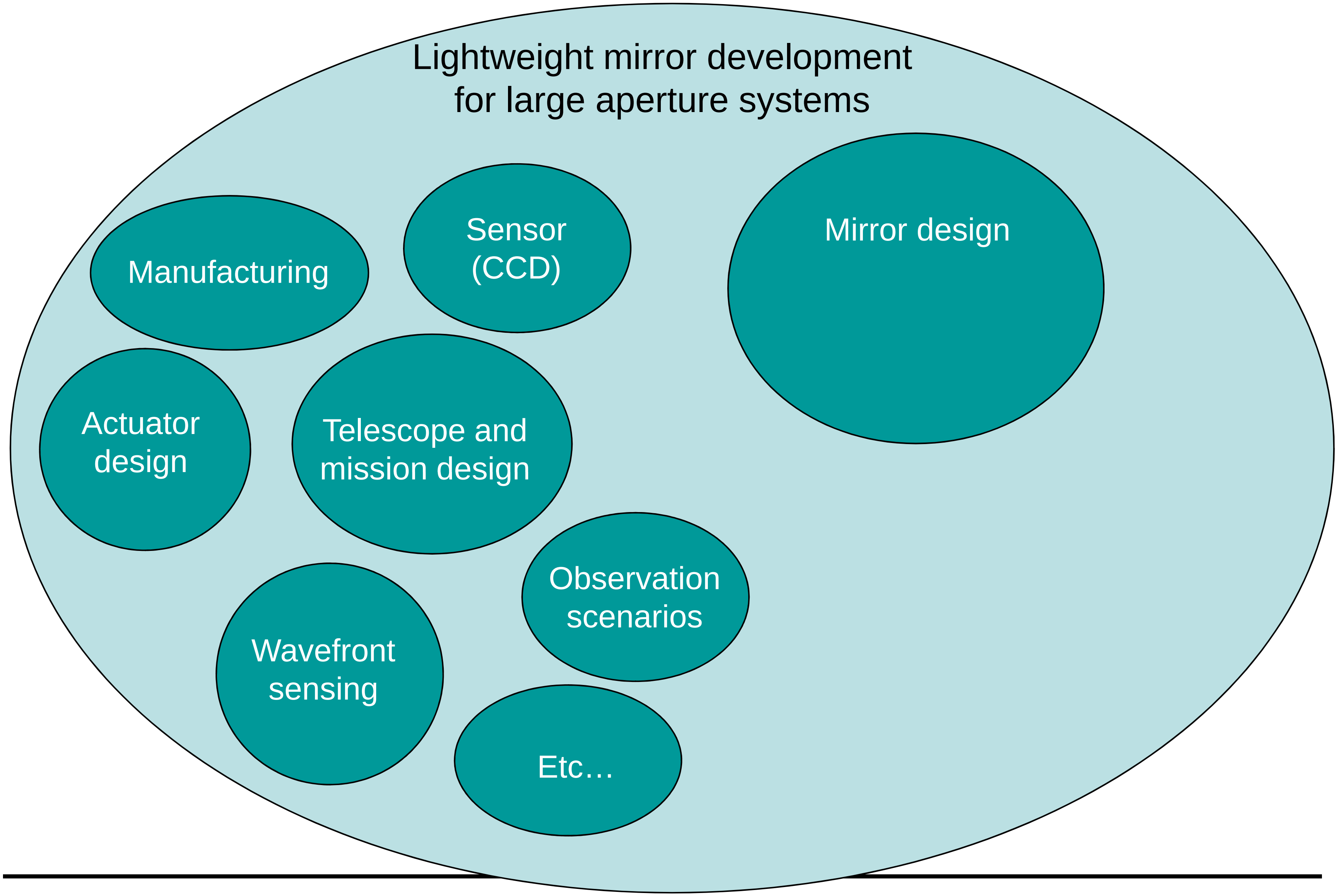
- Multiple disturbance types and environments
- Controlled structure
- High precision (optical tolerances)
- Multidisciplinary (structures, optics, controls, etc.)
- High-fidelity models required



Mirror Model with Embedded Actuators

Using integrated modeling and multidisciplinary optimization

Scope



Lightweight mirror development for large aperture systems

Manufacturing

Sensor (CCD)

Mirror design

Actuator design

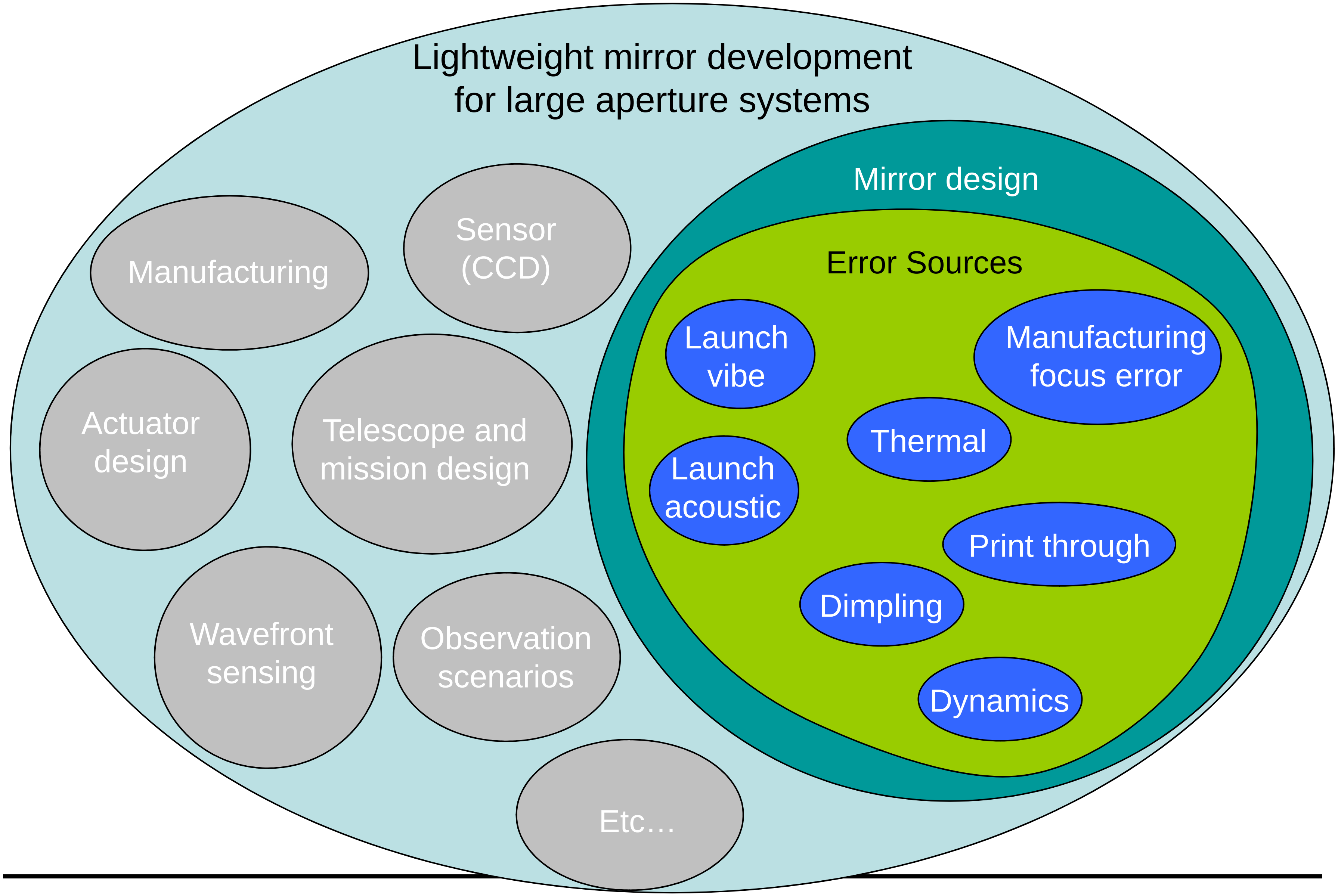
Telescope and mission design

Observation scenarios

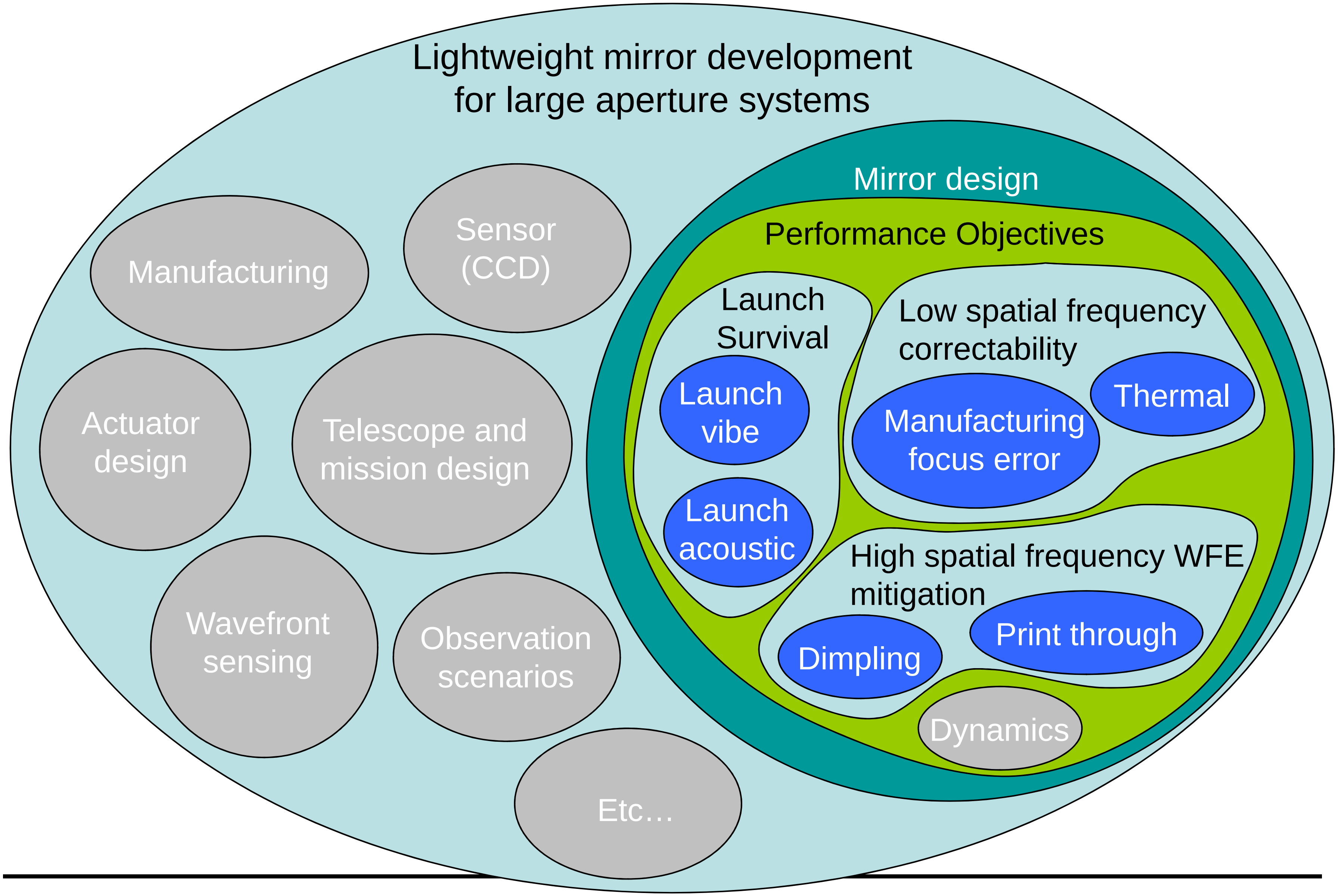
Wavefront sensing

Etc…

Scope


Lightweight mirror development
for large aperture systems
Manufacturing
Sensor (CCD)
Actuator design
Telescope and mission design
Wavefront sensing
Observation scenarios
Etc…
Mirror design
Error Sources
Launch vibe
Manufacturing focus error
Thermal
Launch acoustic
Print through
Dimpling
Dynamics

Scope



Lightweight mirror development for large aperture systems

Manufacturing

Sensor (CCD)

Actuator design

Telescope and mission design

Wavefront sensing

Observation scenarios

Etc…

Mirror design

Performance Objectives

Launch Survival

Launch vibe

Launch acoustic

Low spatial frequency correctability

Manufacturing focus error

Thermal

High spatial frequency WFE mitigation

Dimpling

Print through

Dynamics

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

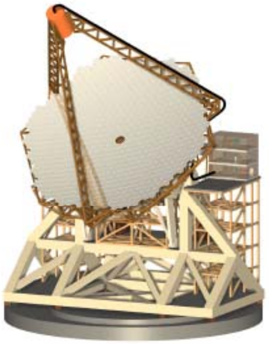
Modeling and Optimization
- Parametric, integrated modeling
- Multidisciplinary optimization
- Model reduction
- Model validation

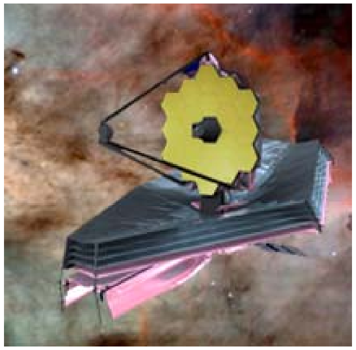
Controlled Structures
- MACE
- Robust Controls
- Shape control

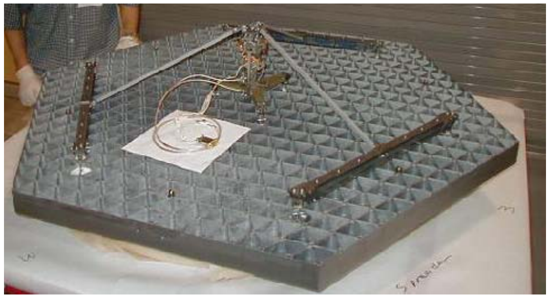
Launch
- Environment
- Analysis
- Alleviation

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
- Lighweight 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

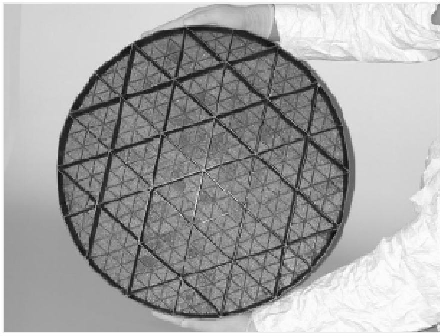






AMSD Beryllium Mirror - Stahl

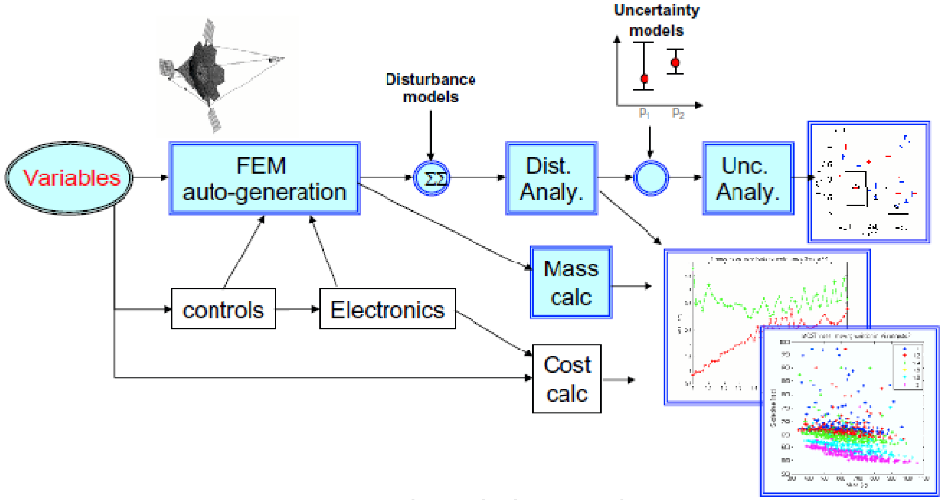
Mirror & Embedded Actuators (Separated) - MacEwen



Silicon Carbide Mirror - Ealey

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



Uncertainty models

Disturbance models

Variables

FEM auto-generation

ΣΣ

Dist. Analy.

Unc. Analy.

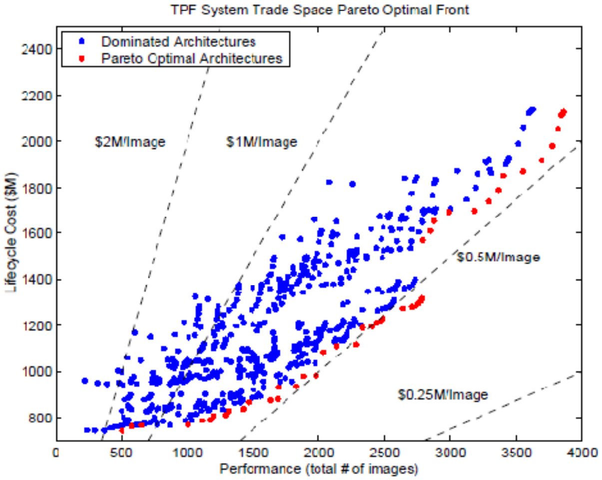
Mass calc

controls

Electronics

Cost calc

MOST Integrated Modeling Environment - Uebelhart



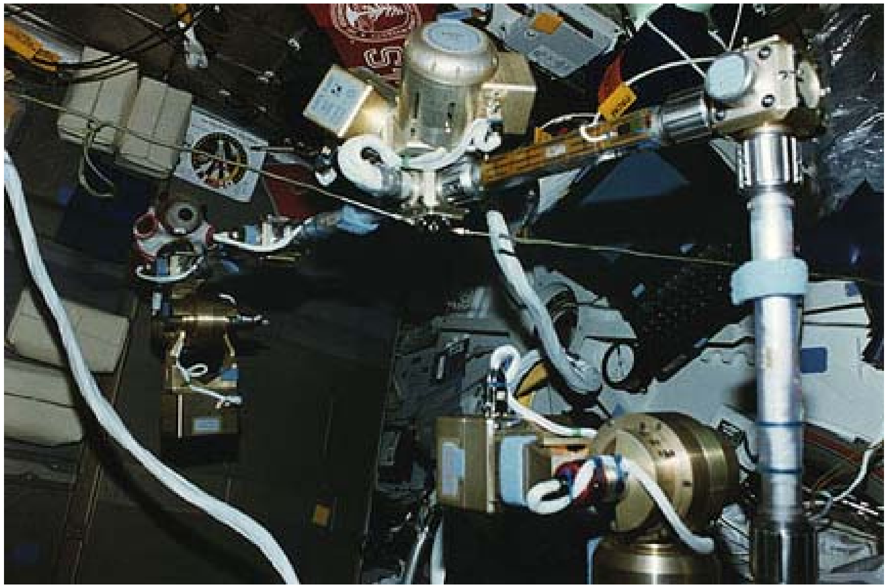
TPF Trade Space Exploration and Optimization - Jilla

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

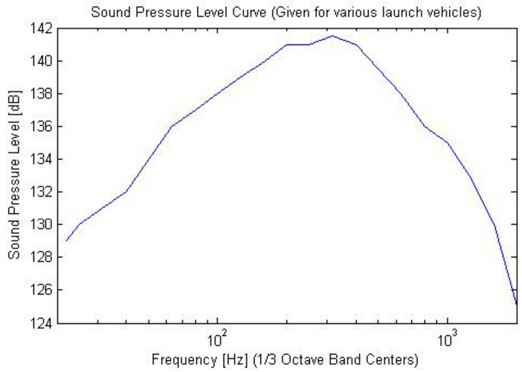
- MACE (Middeck Active Control Experiment) (Miller, Crawley, How, Liu, Campbell, Grocott, Glaese, etc.)
  - SERC flight experiment in 1995
    - Modeling (FEM and measurement based)
    - System ID
    - Robust controls
    - Uncertainty analysis
- Robust controls (Zhou & Doyle, Grocott, How)
  - Control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

MACE



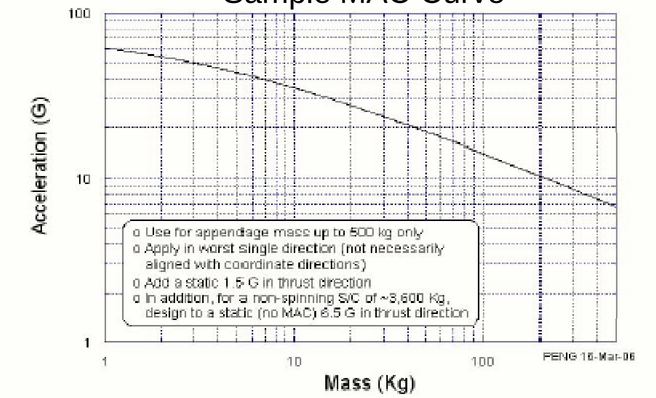
Literature Review – Launch

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

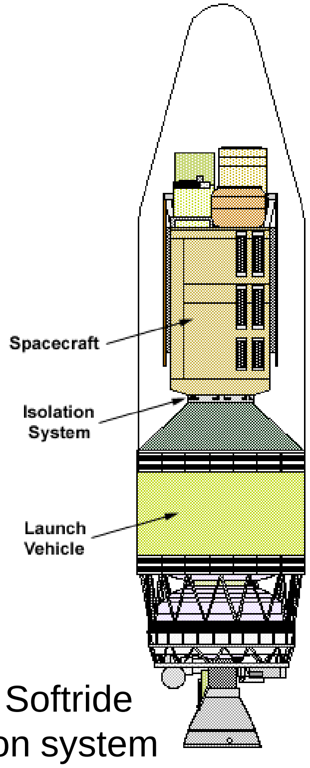


- Analysis (Kabe, Trubert, Sarafin)
  - Coupled loads analysis
  - Mass Acceleration Curve (MAC)

Sample MAC Curve



- 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

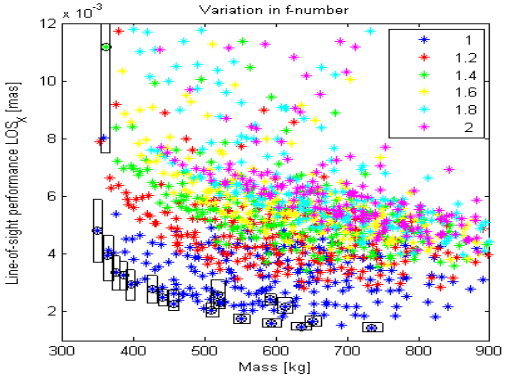


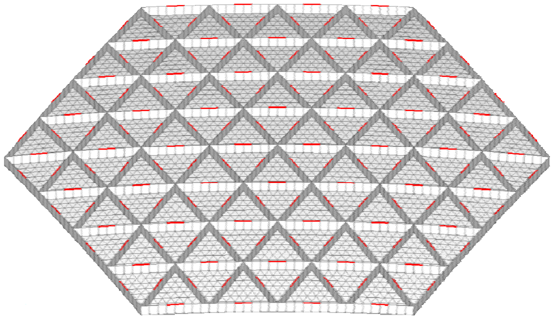
CSA Softride isolation system

Background: MOST Project

Objectives

- Explore the trade space of space telescope design through parametric, integrated modeling
- Lightweight, actuated mirror design and control

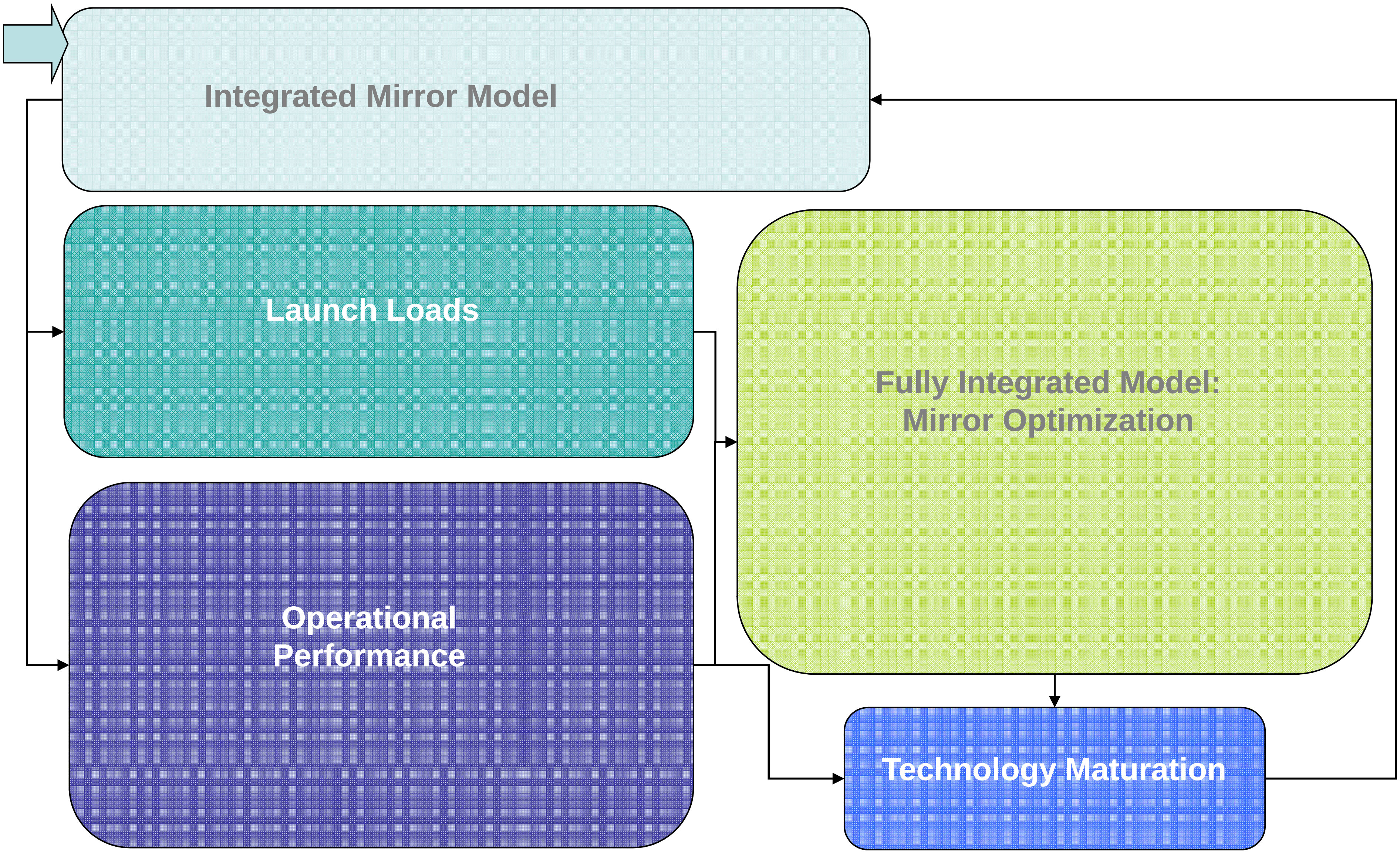




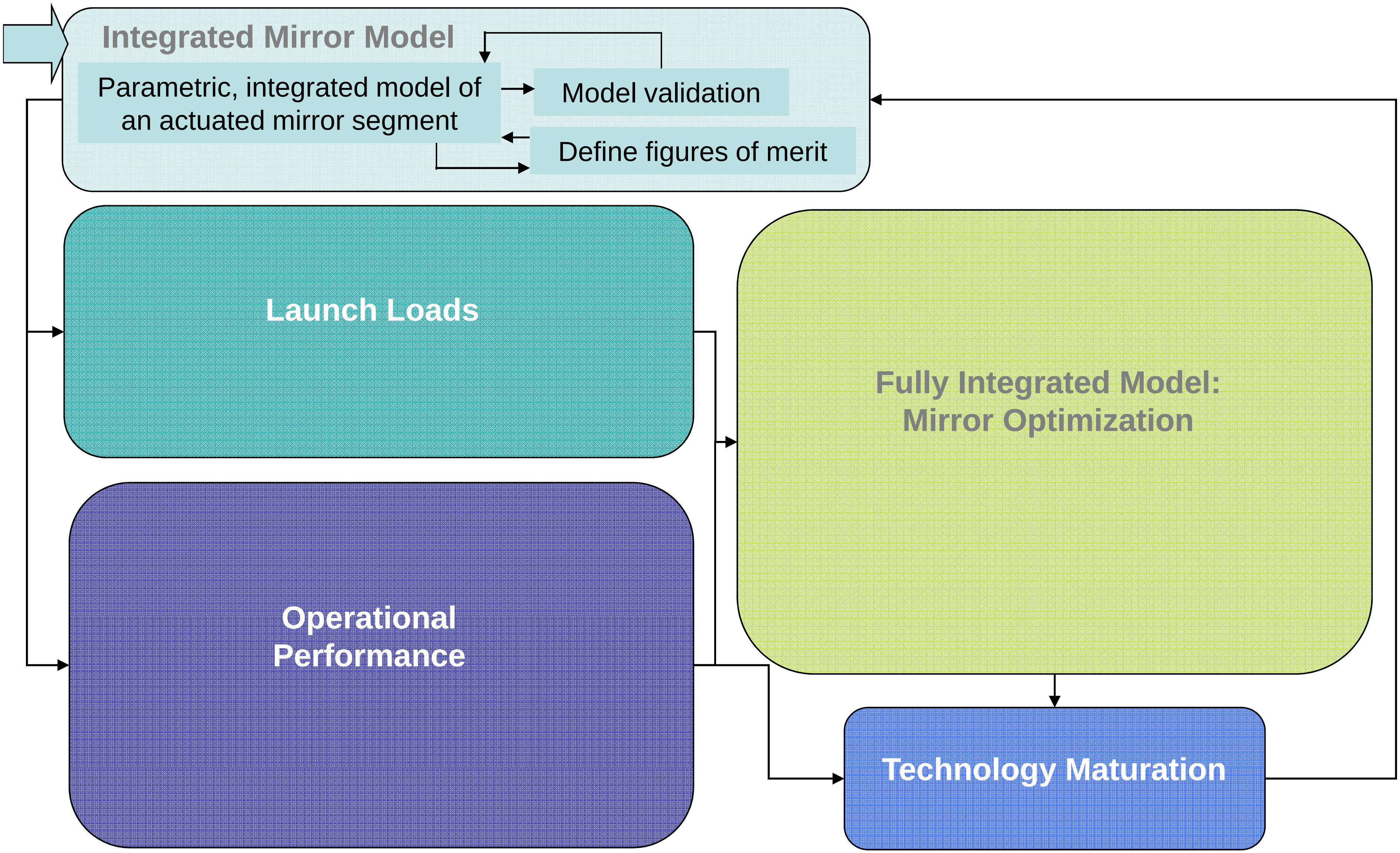
Relevant Work

- 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



Approach: Overview



Integrated Mirror Model

Parametric, integrated model of an actuated mirror segment

Model validation

Define figures of merit

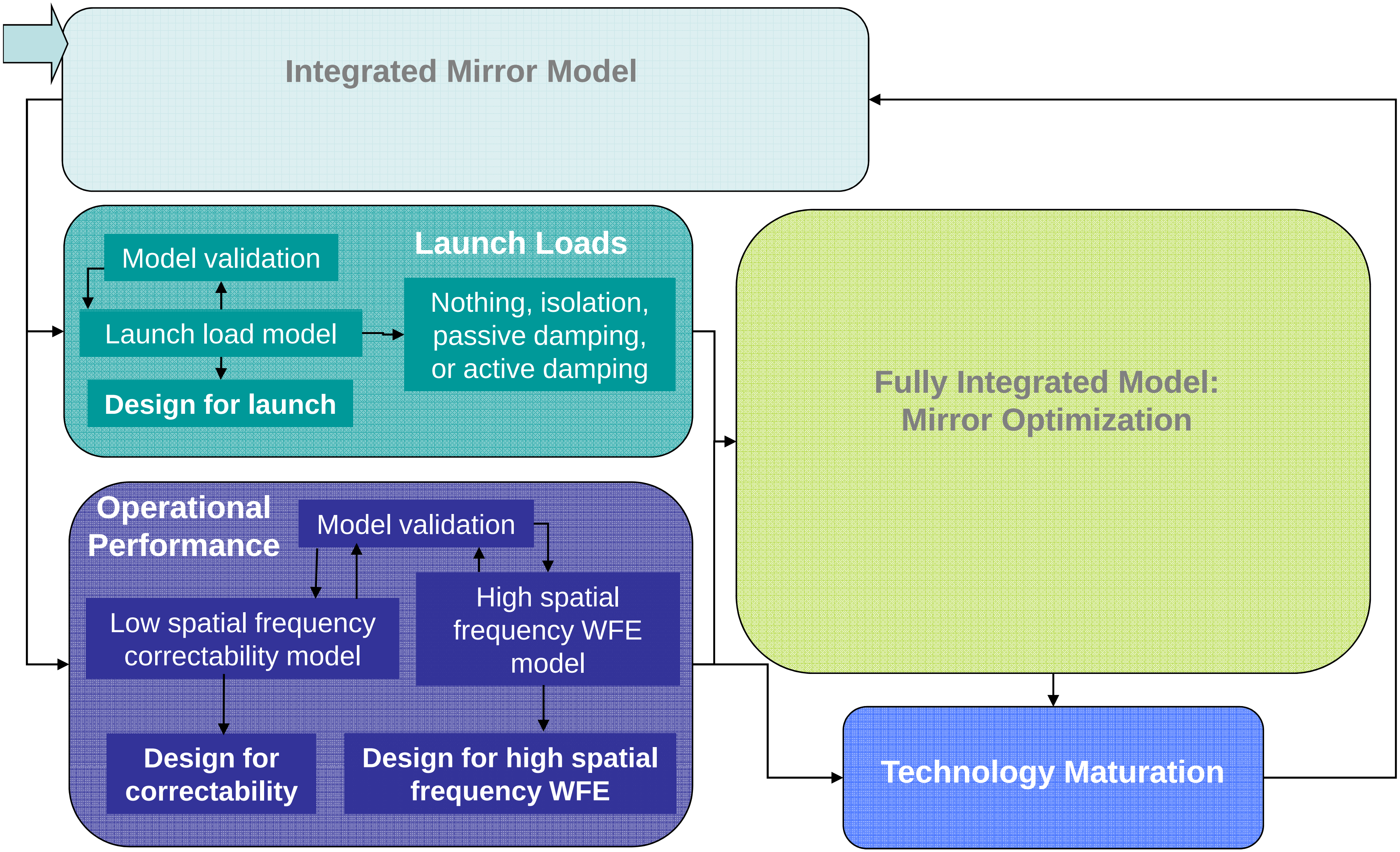
Launch Loads

Fully Integrated Model: Mirror Optimization

Operational Performance

Technology Maturation

Approach: Overview



Integrated Mirror Model

Launch Loads

Model validation

Launch load model

Design for launch

Nothing, isolation, passive damping, or active damping

Operational Performance

Model validation

Low spatial frequency correctability model

High spatial frequency WFE model

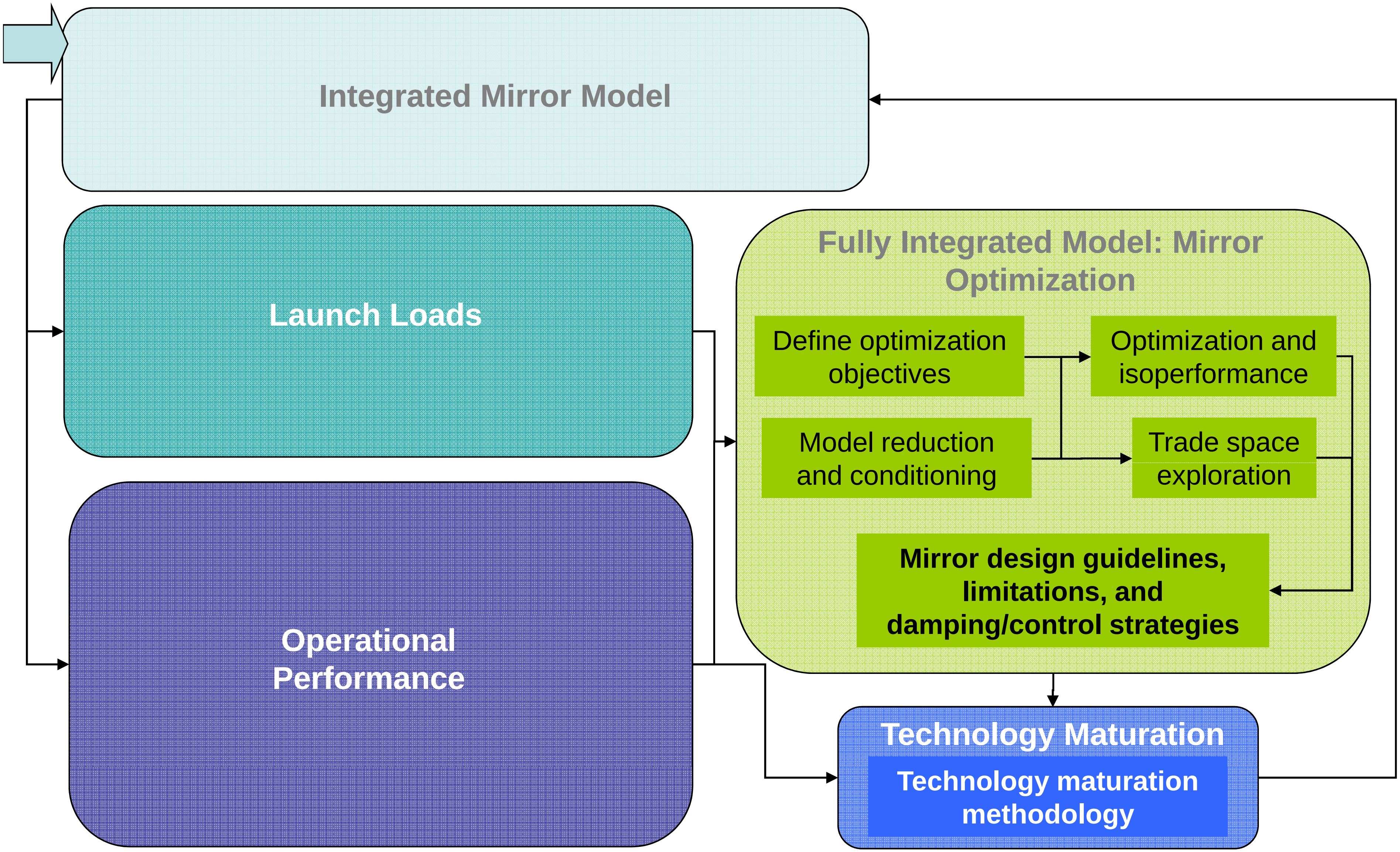
Design for correctability

Design for high spatial frequency WFE

Fully Integrated Model: Mirror Optimization

Technology Maturation

Approach: Overview



Integrated Mirror Model

Launch Loads

Operational Performance

Fully Integrated Model: Mirror Optimization

Define optimization objectives

Model reduction and conditioning

Optimization and isoperformance

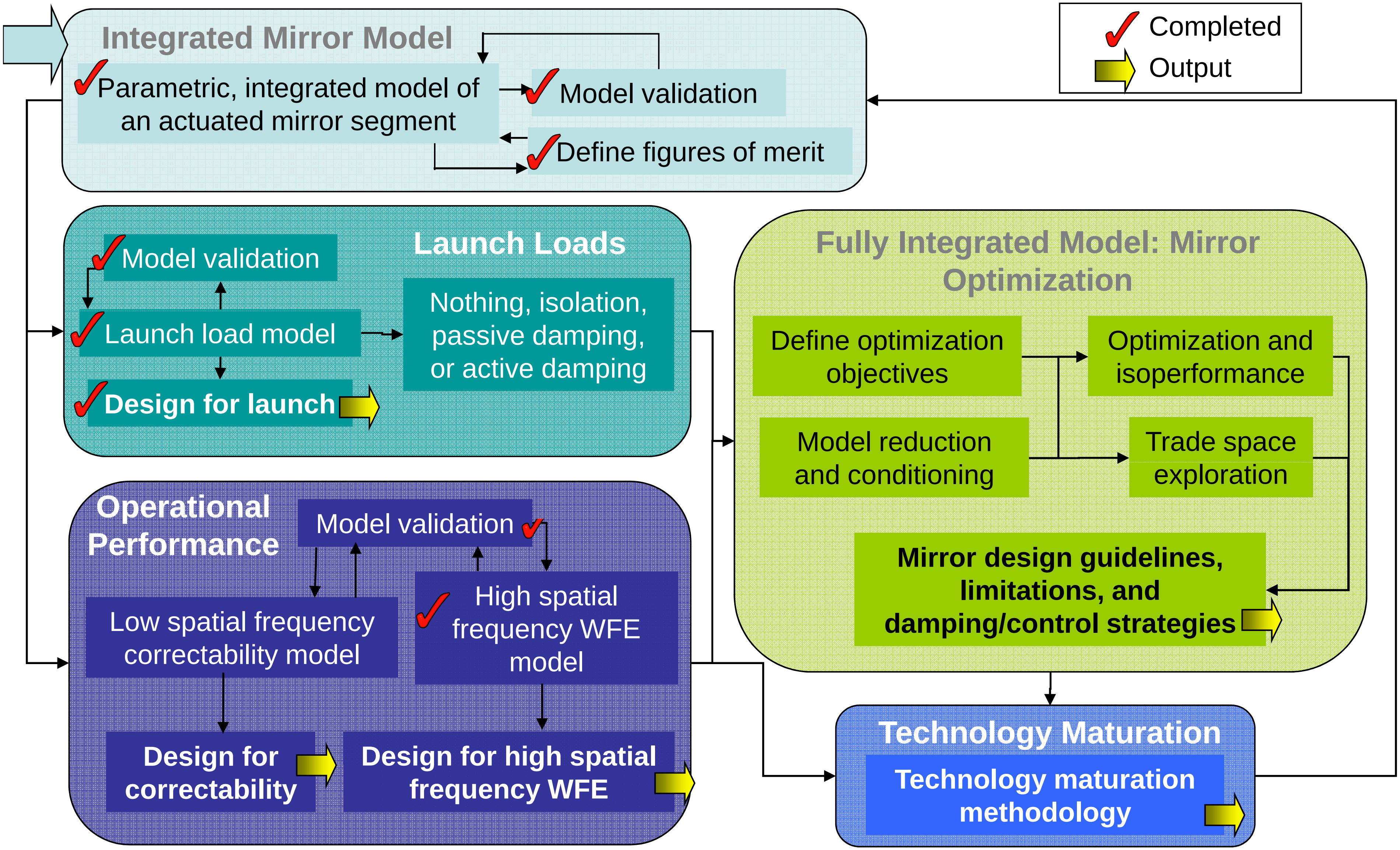
Trade space exploration

Mirror design guidelines, limitations, and damping/control strategies

Technology Maturation

Technology maturation methodology

Approach: Overview



✓ Completed
⇨ Output

Integrated Mirror Model

✓ Parametric, integrated model of an actuated mirror segment

✓ Model validation

✓ Define figures of merit

Launch Loads

✓ Model validation

✓ Launch load model

✓ Design for launch ⇨

Nothing, isolation, passive damping, or active damping

Operational Performance

Model validation ✓

Low spatial frequency correctability model

✓ High spatial frequency WFE model

Design for correctability ⇨

Design for high spatial frequency WFE ⇨

Fully Integrated Model: Mirror Optimization

Define optimization objectives

Optimization and isoperformance

Model reduction and conditioning

Trade space exploration

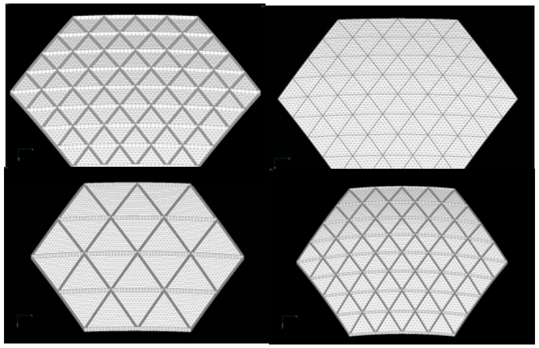
Mirror design guidelines, limitations, and damping/control strategies ⇨

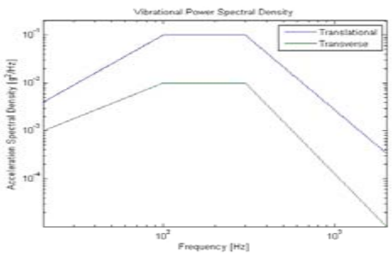
Technology Maturation

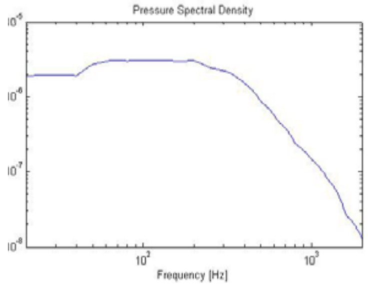
Technology maturation methodology ⇨

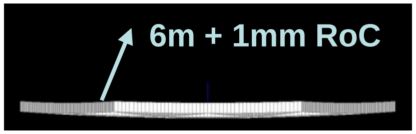
Approach: Integrated Model Development

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









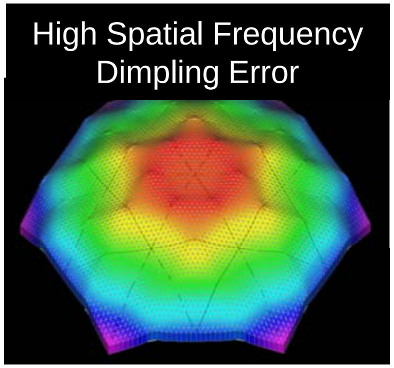
Disturbance models

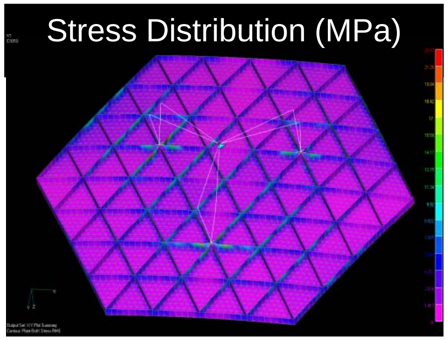
Define FEM grid points, element connectivities, material properties, etc.

FEM normal modes analysis

State-space modeling

Disturbance analysis

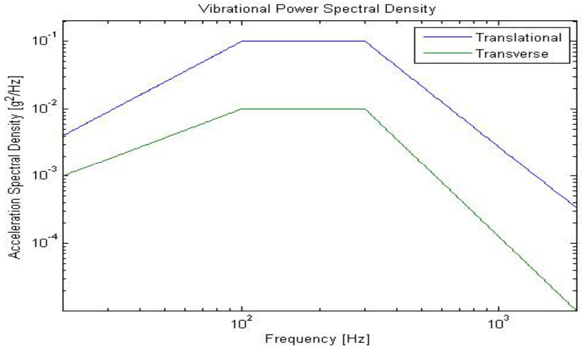




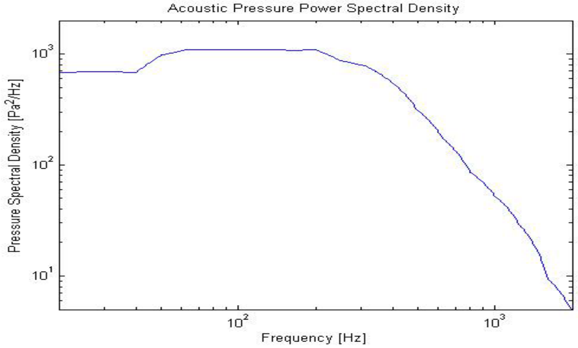
Performance outputs

Approach: Launch Loads

Vibration PSD



Acoustic PSD



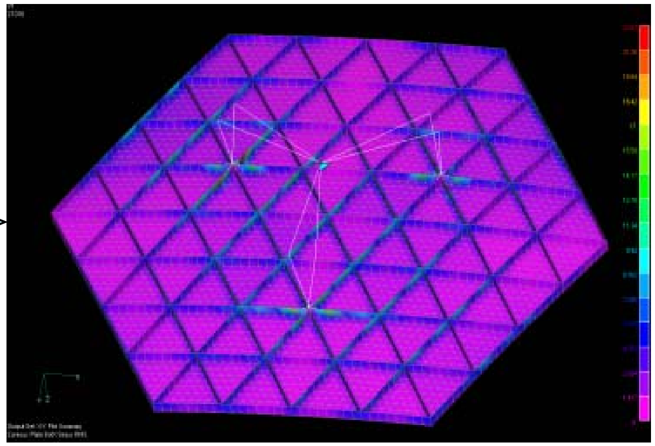
Normal modes analysis

Interpolation functions

Model manipulation

Disturbance analysis

Stress Distribution

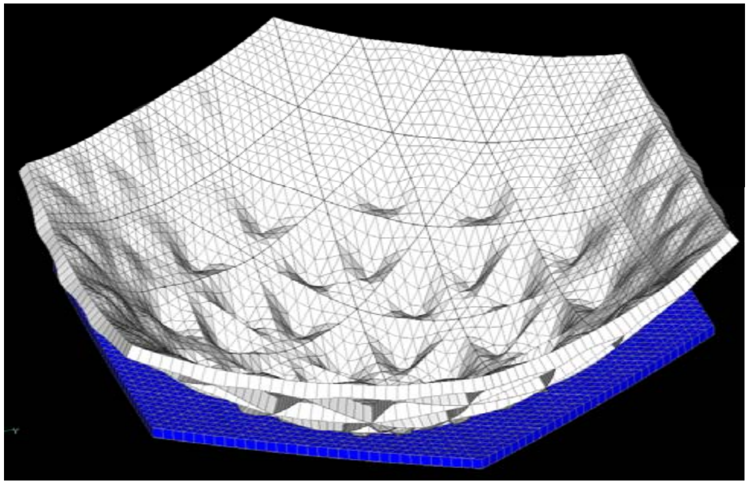


- Dynamic formulation (state-space)
- Launch load alleviation:
  - Isolation
  - Passive damping using embedded actuators as shunted piezoelectrics
  - Active damping with embedded actuators and robust control methods

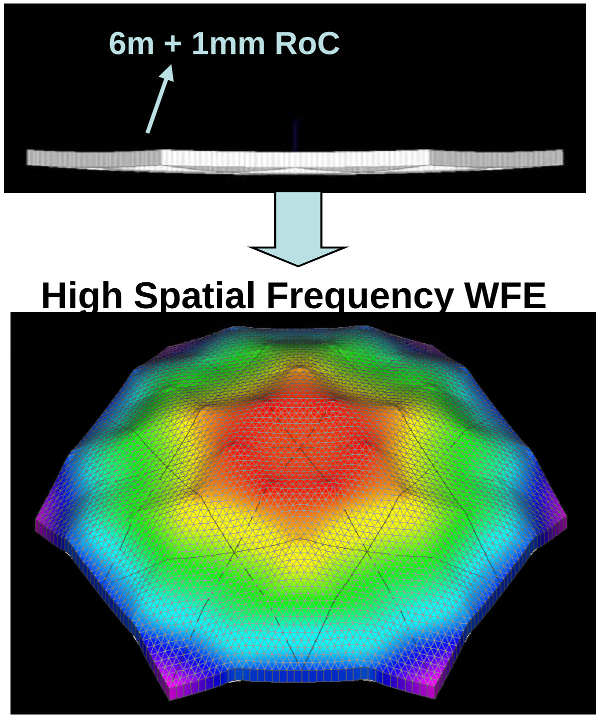
Approach: Operational Performance

- 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



Induced focus command



High Spatial Frequency WFE

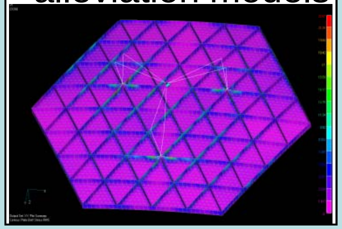
Control:

- Quasi static
- Based on influence functions
- Least-squares

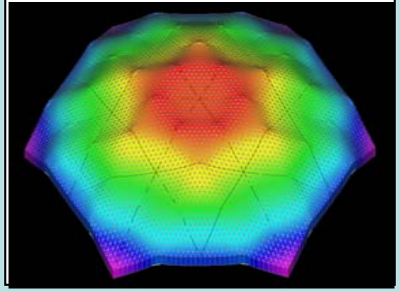
Approach: Mirror Optimization

Mirror Model

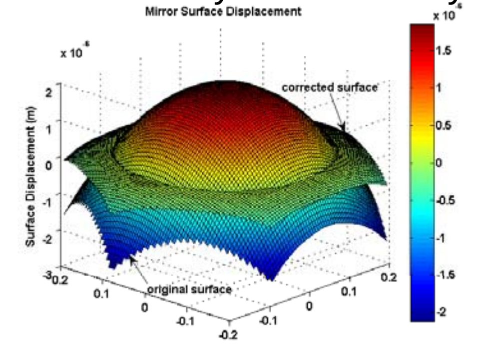
Launch stress and alleviation models



High spatial frequency error models



Correctability/Controllability



Combine models of various design components
- Launch
- Operational performance

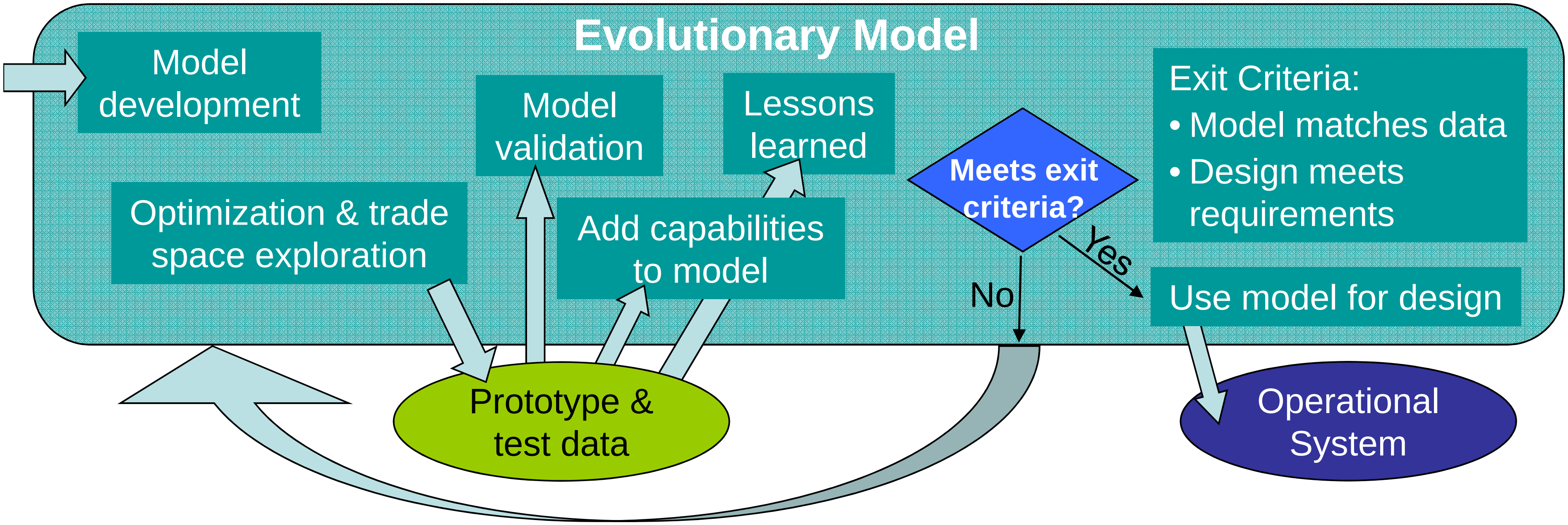
Model Reduction
- Circulance
- Balanced Reduction
- Others

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

Objective Functions
- Separable designs (lowest stress, WFE, etc)
- Lowest mass that meets requirements
- Others to be identified

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

Approach: Methodology for Technology Maturation



Evolutionary Model

Model development

Optimization & trade space exploration

Model validation

Lessons learned

Add capabilities to model

Meets exit criteria?

Exit Criteria:
- Model matches data
- Design meets requirements

Use model for design

- 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

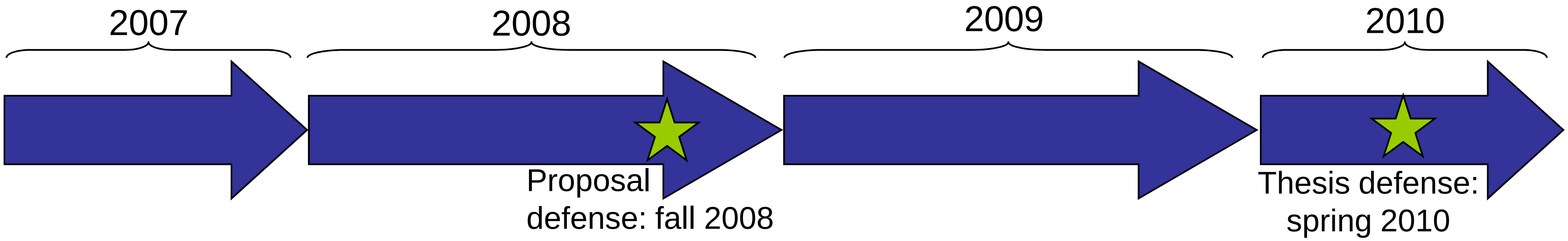
Potential Contributions

- 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

Preliminary Thesis Outline

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



2007

2008

2009

2010

Proposal defense: fall 2008

Thesis defense: spring 2010

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

References (1)

Telescops and Mirrors

- G. Angeli, A. Segurson, R. Upton, B. Gregory, and M. Cho. *Integrated modeling tools for large ground based optical telescopes. In Proceedings of the SPIE*, Volume 5178, pages 49–63. SPIE, 2004
- G. Z. Angeli, J. Dunn, S. C. Roberts, D. G. MacMynowski, A. Segurson, K. Vogiatzis, and J. Fitzsimmons. Modeling tools to estimate the performance of the Thirty Meter Telescope: an integrated approach. In *Proceedings of the SPIE*, Volume 5497, pages 237–250. SPIE, 2004
- J. H. Burge, J. R. P. Angel, B. Cuerden, H. M. Martin, S. M. Miller, and D. G. Sandler. Lightweight mirror technology using a thin facesheet with active rigid support. In *Proceedings of the SPIE, Volume 3356, Space Telescopes and Instrumentation*, pages 690–701. SPIE, 1998
- M. A. Ealey. Fully active telescope. In *UV/Optical/IR Space Telescopes: Innovative Technologies and Concepts*, volume 5166, pages 19–26. SPIE, 2004
- M. A. Ealey. Large optics in the 21st century: a transition from discrete manufacturing to highly integrated techniques. In *IEEE Aerospace Conference*, 2003
- J. W. Hardy. Active optics: A new technology for the control of light. *Proceedings of IEEE*, 66(6):651–697, 1978
- C. F. Lillie and A. J. Bronowicki. Adaptation in space telescopes. In *45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference*, Palm Springs, CA, April 19-22 2007. AIAA 2004-2064
- H. A. MacEwen. Separation of functions as an approach to development of large space telescope mirrors. In *Proceedings of SPIE: UV/Optical/IR Space Telescopes: Innovative Technologies and Concepts*, volume 5166, pages 39–48. SPIE, 2004
- L. E. Matson and D. Mollenhauer. Advanced materials and processes for large, lightweight, space-based mirrors. In *IEEE Aerospace Conference*, March 2003
- H. P. Stahl. JWST lightweight mirror TRL-6 results. In *IEEE Aerospace Conference*, 2007.
- H. P. Stahl and L. Feinberg. Summary of NASA advanced telescope and observatory capability roadmap. In 2007 *IEEE Aerospace Conference*. March 2007
- R. K. Tyson. *Principles of Adaptive Optics*. Academic Press, Inc., San Diego, CA, 1991

References (2)

Modeling and Optimization

- V. Babuska, D. Carter, and S. Lane. Structural vibration modeling and validation: Modeling uncertainty and stochastic control for structural control. Technical report, Air Force Research Lab, 2005. AFRL-VS-PS-TR-2005-1174
- O. Balci. Validation, verification, and testing techniques throughout the life cycle of a simulation study. *Annals of Operations Research*, 53:121–173, 1994.
- J.-F. Barthelemy and R. Haftka. Approximation concepts for optimum structural design - a review. *Structural Optimization*, 5:129–144, 1993
- C. Blaurock. Disturbance-Optics-Controls-Structures (DOCS). Technical report, Nightsky Systems, Inc., 2006. URL: http://www.nightsky-systems.com/pdf/DOCS_Intro.pdf
- O. L. de Weck. *Multivariable Isoperformance Methodology for Precision Opto-Mechanical Systems*. PhD thesis, Massachusetts Institute of Technology, 2001
- V. Genberg, K. Doyle, and G. Michaels. Optical interface for MSC.Nastran. In *MSC VPD Conference*, 2004.
- S. O. Grocott. *Dynamic Reconstruction and Multivariable Control for Force-Actuated, Thin Facesheet Adaptive Optics*. PhD thesis, Massachusetts Institute of Technology, 1997
- R. T. Haftka. Integrated structure-control optimization of space structures. In *AIAA Dynamics Specialists Conference*, Long Beach, CA, 1990
- C. D. Jilla. *A Multiobjective, Multidisciplinary Design Optimization Methodology for the Conceptual Design of Distributed Satellite Systems*. PhD thesis, Massachusetts Institute of Technology, Cambridge, MA, May 2002
- R. A. Masterson. *Dynamic Tailoring and Tuning for Space-Based Precision Optical Structures*. PhD thesis, Massachusetts Institute of Technology, February 2005.
- B. C. Moore. Principal component analysis in linear systems: Controllability, observability, and model reduction. In *IEEE Transactions on Automatic Control*, volume 26, 1981
- T. D. Robinson. Surrogate-Based Optimization using Multifidelity Models with Variable Parameterization. PhD thesis, Massachusetts Institute of Technology, 2007
- J. Sobieszczanski-Sobieski and R. T. Haftka. Multidisciplinary aerospace design optimization: survey of recent developments. *Structural Optimization,* 14:1–23, 1997
- S. A. Uebelhart, L. E. Cohan, and D. W. Miller. Design exploration for a modular optical space telescope architecture using parameterized integrated models. In *47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference*, Newport, RI, May 1-4, 2006. AIAA 2006-2083
- S. A. Uebelhart. *Non-Deterministic Design and Analysis of Parameterized Optical Structures during Conceptual Design*. PhD thesis, Massachusetts Institute of Technology, June 2006.
- K. Willcox and J. Peraire. Balanced model reduction via the proper orthogonal decomposition. *AIAA Journal*, 40(11):2323–2330, 2002

References (3)

Controlled Structures

- B. N. Agrawal and K. E. Treanor. Shape control of a beam using piezoelectric actuation. *Smart Materials and Structures*, 8:729–740, 1999
- M. E. Campbell and S. C. O. Grocott. Parametric uncertainty model for control design and analysis. *IEEE Transactions on Control Systems Technology*, 7(1):85–96, January 1999
- E. Crawley, M. Campbell, and S. Hall. *High Performance Structures: Dynamics and Control*. Cambridge University Press - Draft, Cambridge, MA, 1998
- E. F. Crawley, B. P. Masters, and T. T. Hyde. Conceptual design methodology for high performance dynamic structures. In *AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and Exhibit*, 1995. AIAA-1995-1407
- S. O. Grocott. Comparison of control techniques for robust performance on uncertain structural systems. Master's thesis, Massachusetts Institute of Technology, Cambridge, MA, February 1994
- S. O. Grocott. *Dynamic Reconstruction and Multivariable Control for Force-Actuated, Thin Facesheet Adaptive Optics*. PhD thesis, Massachusetts Institute of Technology, 1997
- J. P. How, S. R. Hall, and W. M. Haddad. Robust controllers for the Middeck Active Control Experiment using Popov controller synthesis. In *IEEE Transactions on Control System Technology*, volume 2, 1994
- J. How. *Robust Control Design with Real Parameter Uncertainty using Absolute Stability Theory*. PhD thesis, Massachusetts Institute of Technology, 1993
- H. Irschik. A review of static and dynamic shape control of structures by piezoelectric actuation. *Engineering Structures*, 24:5–11, 2005
- K. Liu, R. N. Jacques, and D. W. Miller. Frequency domain structural system identification by observability range space extraction. In *Proceedings of the American Controls Conference*, pages 107–111, June 1994
- D. W. Miller, E. F. Crawley, J. P. How, K. Liu, M. E. Campbell, S. C. O. Grocott, R. M. Glaese, and T. D. Tuttle. The Middeck Active Control Experiment (MACE): Summary report. Report 7-96, MIT Space Engineering Research Center, 1996
- K. Zhou and J. C. Doyle. *Essentials of Robust Control*. Prentice Hall, New Jersey, 1998.

References (4)

Launch

- A. S. Bicos, C. Johnson, and L. P. Davis. Need for and benefits of launch vibration isolation. In *Proceedings of the SPIE*, Vol 3045, 1997
- CSA Engineering. Softride launch environment mitigation. http://www.csaengineering.com/spclnch/spacelaunch.asp
- R. M. Glaese. *Impedance Matching for Structural-Acoustic Control*. PhD thesis, Massachusetts Institute of Technology, April 1997
- S. Griffin, S. A. Lane, C. Hansen, and B. Cazzolato. Active structural-acoustic control of a rocket fairing using proof-mass actuators. *Journal of Spacecraft and Rockets*, 38:219–225, 2001
- N. W. Hagood and A. V. Flotow. Damping of structural vibrations with piezoelectric materials and passive electrical networks. *Journal of Sound and Vibration*, 146(2):243– 268, 1991
- A. M. Kabe. Design and verification of launch and space vehicle structures. In *AIAA Structures, Dynamics and Materials Conference*, number AIAA-98-1718, 1998
- D. J. Leo and E. H. Anderson. Vibroacoustic modeling of a launch vehicle payload fairing for active acoustic control. In *AIAA Structures, Dynamics, and Materials Conference*, number AIAA-98-2086, pages 3212–3222. AIAA, 1998
- S. O. R. Moheimani. A survey of recent innovations in vibration damping and control using shunted piezoelectric transducers. In *IEEE Transactions on Control Systems Technology*, volume 11, 2003.
- T. P. Sarafin, editor. *Spacecraft Structures and Mechanisms - From Concept to Launch*. Microcosm, Inc. and Kluwer Academic Publishers, 1995
- M. Trubert. Mass acceleration curve for spacecraft structural design. Technical report, NASA Jet Propulsion Lab, November 1989. JPL D-5882