Fine Steering Mirror for Smallsat Pointing and Stabilization

Dr. Steve Wassom, PI
Morgan Davidson, Presenter
Trent Newswander
James Cook
Zach Casper
Adam Shelley

Space Dynamics
L A B O R A T O R Y
Utah State University Research Foundation

Outline

- Introduction
- Justification and SDL experience
- Requirements and trades
- Design description
- Structural/thermal analysis
- Control system development
- Test results and model validation
- Performance summary
- Future work

Introduction

- **Fine Steering Mirror** (FSM) Prototype built by SDL
- **Enabling technology** for small-sats
- Low-cost **two-axis** mechanism
- Financed by internal funds
- Unique feedback sensor
- Large angular deflection
- **High bandwidth**

Justification

- **Move the boresight – not the bus!**
- Payloads can achieve better coverage
- Space-rated FSMs too pricey for some smallsat programs
- **Low-cost** space FSM an **enabling technology** for smallsats

$$$

Space Dynamics
LABORATORY
Utah State University Research Foundation

Prior FSM Experience at SDL

SDL-Built Steering Mirrors
• SABER – Single axis scan mirror, over 4 years on-orbit
• CAJIS – Single axis fast steering mirror, 300 Hz response, magnetostrictive actuator

SDL Programs Incorporating Others' Steering Mirrors
• SOFIE
• GIFTS
• WISE
• SPIRIT III

FSM Requirements

Generic requirements based on management consensus

- Two-axis scan mirror
- Space operation
- Low cost
- **Azimuth deflection:** ±60 degrees mechanical
- **Elevation deflection:** ±15 degrees mechanical
- **Position accuracy:** 1-2 arcsec
- **Clear aperture:** 75 mm
- **Bandwidth:** 70-100 Hz
- **Operating temp:** down to 210 K
- **Mirror RMS WFE (flatness):** <1/10 wave HeNe
- **Mirror RMS surf. roughness:** < 20 angstroms

Mechanism Trade-offs

	Bearings	Actuators	Feedback Sensors
Azimuth	***Ball Bearings*** Gas Bearings	***Brushless DC*** Stepper	***Optical Encoder*** Resolver Inductosyn
Elevation	Ball Bearings ***Flex Pivots*** Flexures	Piezo Magnetostrictive ***Voice Coil*** Brushless DC Stepper	Optical Encoder ***Inductive*** Capacitive Strain Gage Resolver Inductosyn

Mirror Design

- Flat **aluminum** mirror
- Clear aperture: 75 mm x 150 mm **Ellipse** shape
- Open back form for lightweight and thermal
- Triangular cells considered optimum geometry
- Mounting on four **flexure isolated pads**
- Single point diamond turned face
- VQ Post-polishing
- Operating temperature: **210 K**
- Mirror mass: 0.16 kg

Triangular Cell
Open-Back Design

Azimuth Axis Design

- **Brushless DC** motor
- Ball bearings
- **Optical encoder**
- 4.5 arcsec per encoder count
- Similar to SABER design

Elevation Axis Design

- Yoke supported by Az shaft
- **Flex pivots**
- Pivot life virtually infinite
- Pivots sized for assumed launch loads
- Rotary **voice coil** motor
- **Unique feedback sensor**

Wedge Sensor

- Tapered **wedge** moves between **opposed inductive transducers**
- Minimizes effects of wobble, vibration
- Good resolution, repeatability
- Some drift with temperature
- Can be temperature-mapped
- Provisional **patent** secured

Electronics Design

Azimuth axis
- COTS Linear brushless servo amplifier
- Sinusoidal commutation done in real-time software
- COTS optical encoder interfaced to real-time environment

Elevation axis
- Wedge sensor interfaced to real-time environment
- COTS power op-amp driver circuit
- Built by SDL

Thermal Design

Two main challenges
- Maintain mirror at minimum temperature
- Minimize thermal gradients across mirror

Solutions
- Thermal coatings
- Thermal isolation
- Cool baffle with azimuth shaft passing through
- Mirror thermally isolated on elevation flex pivots

Mirror Analysis

- Mirror modal – 1st mode at 270 Hz
- Mirror mounting distortion – 1/20th wave HeNe (RMS)
- Mirror thermal elastic – 1/30th wave HeNe (PV)
- Mirror face thermal gradient (LEO) – 0.11 K

Figure 8. Mirror Mode 1, Torsional About Z-Axis, 270 Hz

Figure 11. Predicted Surface Normal

Figure 12. Sag (meters) of Optical Surface due to Thermal Elastic Deformation

Mirror Test Results

- Bell jar test chamber
- Zygo Fizeau interferometer
- Mounting distortion – 1/40th wave HeNe (RMS)
- WFE (flatness) at 210 K – 1/12th wave HeNe (RMS)
- Rib print-through not detectable down to 92 K
- Vendor is confident SPDT marks seen in the interferogram will not be in future mirrors

Figure 20. Interferometric Measurements at 292K

Figure 21. Interferometric Measurements at 186K

Control System Development

- Rapid Prototyping Methodology
  - Based on COTS software tools
  - Customized for optical pointing
  - End-to-end modeling of dynamics, controls, optics
  - Automatic code generation
  - Real-time HIL testing
  - Customized GUI for "on-the-fly" tweaking
  - Substantial time-money savings
- Multi-body dynamics model
  - Rigid body representations
  - Flexible body representations
  - Co-simulated with controls model

1. LOS Control Problem & Requirements Definition → 2. Physical & Empirical Plant Modeling & Visualization → 3. Control Algorithm Design, Analysis, Simulation & Visualization

ITERATIONS & REFINEMENTS

6. Full System Verification via Embedded Code Testing ← 5. Subsystem Verification via Hardware-in-the-Loop Simulation/Testing ← 4. Automatic Code Generation, Real-Time Simulation & Visualization

Control System Test Results

- Small and large angle step response tests
- Used control systems analyzer for frequency response
- Sine sweep (100 arcsec) from 1 Hz to 1000 Hz
- System components characterized individually
- Model results match well with test data

Figure 23. Azimuth Axis Large-Angle Step Response

FSM Performance

Specification	Value	Comments
Aperture (mm)	75	At 60 incident degree angle
Mirror RMS WFE (waves HeNe)	1/12	Measured at 210K
Mirror Surface RMS roughness (angstroms)	20	
Mass (kg)	1.0	Electronics not included
Avg. Power (W)	0.4	Continuous GMC scans
Peak Power (W)	30	Simultaneous large-angle steps
Azimuth Rot. (mechanical deg)	±60	
Elevation Rot. (mechanical deg)	±15	
Azimuth Error Mean (arcsec)	<1	Last 10 s of step-and-hold
Azimuth Error Std. Dev. (arcsec)	<3	One encoder count = 4.5 arcsec
Elevation Error Mean (arcsec)	<0.05	Due to transducer repeatability
Elevation Error Std. Dev. (arcsec)	<6.5	Mainly due to A/D card
Azimuth Slew Rate (0-100%) (deg/sec)	160	
Elevation Slew Rate (0-100%) (deg/sec)	75	
Bandwidth (Hz, 100 arcsec amplitude)	70	-3 dB point
Gain Margin (dB)	6	Could actually be higher

Future Work

Future Work

- Optimize control algorithms
- Improve wedge sensor implementation
- Upgrade and package electronics
- Move to all space-rated components
- Develop command protocols
- Implement launch lock
- Funding secured for this year's effort

Summary

- Introduction
- Justification and SDL experience
- Requirements and trades
- Design description
- Structural/thermal analysis
- Control system development
- Test results and model validation
- Performance summary
- Future work

Questions

?