SFR Team SAVI
Satellite Active Vibration Inverter

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Project Purpose

Cryocoolers create Exported Forces and Torques (EFTs)
- Frequencies dynamically range from 40 to 60 Hz
- Amplitudes on the order of 20 microns (twice the thickness of a sheet of paper)

Simulated Telescoping Camera Payload
- 3.2 kg simulated mass
- 1 μrad Pixel Resolution

Image Smearing
- Pixel Movement
  - Angular Displacements from EFTs

These EFTs will cause up to 150 pixel smear

1- Cryocooler
2- Simulated camera payload
3- SAVI system

- Develop a Satellite Active Vibration Inverter (SAVI) mount system that will identify and cancel low frequency vibrations from a cryocooler that cause image smearing on a telescopic camera.

*objects not to scale
As a camera experiences rotation the image seen by a single pixel may change to another pixel while the shutter is open, causing a smeared image.

On the left shows a single pixel smear. A set of pixels (1, 2, 3) is rotated by \( \theta \), the object seen by pixel2 is then also seen briefly by pixel1 while the shutter is open.
CONOPS

A FFT of the data is done, and displacement is calculated from the acceleration data. Then they are compared to find SAVI’s needed actuation.

Project Purpose
Design Description
Test Overview
Test Results
Systems Engineering
Project Management

*objects not to scale
Levels of Success

Level 1:
- Pixel smear reduced by 60% to about 60 pixels of smear

Level 2:
- Pixel smear reduced by 80% so that about 30 pixels or fewer are smeared
- Disturbance frequency has dwell time of 2 seconds and reduction meets Level 1

Level 3:
- The system dimensions will not exceed 20 cm x 20 cm x 10 cm
- The system mass will not exceed 5 kg
- The system will use no more than 10 W of power
Updates

• Polytec PDV100 Vibrometer
  • 1 week rental donation from Polytec
  • All system testing to be completed in this 1 week

• Mechanical Engineering MEMS lab
  • Testing can be done in MEMS lab on vibration isolated air-table due to acquisition of vibrometer
  • Mounting holes drilled in test stand to allow for solid mounting to air table
SAVI Full System

- cDAQ connected to laptop
- cDAQ D/A and A/D Converter
- Wires to 24 Volt Power Supply
- Electronics Communication and Control Box
- SAVI, Test Stand and Simulated Mass
- Charge Amplifier and Signal Conditioner
- Signal Conditioner

Test Results Systems Engineering Project Management
SAVI Dimensions

- Flexures placed on top and bottom of actuating legs to avoid shear stresses on piezoelectric actuators
- Flexures placed on top of solid leg to allow for plate rotation
- Accelerometers placed on top plate next to each leg and on bottom plate next to the two actuating legs

Mass
- Simulated Payload: 3.2 kg
- SAVI: 1.1 kg
- Test Stand: 1.1 kg
Functional Block Diagram

- **EFT Applied To SAVI via Test Mount**
- **Start SAVI Systems**
- **Initialize cDAQ and Assign Modules in Matlab**
- **Accelerometer Voltage Output**
  - To P-820.20 Piezo Actuator
- **cDAQ**
  - NI 9204
  - Sample voltage at 32.768 kHz
  - New Samples > 8192
  - No
  - Yes
- **NI 9263**
  - Convert Digital input to Analog Voltage V ∈ [0, 0.5)

**MATLAB**

- **Find Amplitude and Frequency using FFT output**
  - Cross Correlation to find Phase
  - FFT
  - Construct Analytical Acceleration Sinusoid
  - Compute Corresponding Displacement
  - Compare to Solid Leg and find desired Piezo Actuator Displacement
  - Compute Voltage Required to displace Piezo Actuator
Amplitude and Frequency Determination

- Frequency Resolution ($df$) of FFT is:
  \[ df = \frac{1}{T} = \frac{1}{\text{time sampled}} = \frac{1}{0.25 \text{ s}} = 4 \text{ [Hz]} \]

- Due to low frequency resolution, peak in frequency domain is spread among many frequencies
  - Summation of amplitudes ($A_i$) around the peak ($j$) gives the actual amplitude prediction ($A$)
    \[ A = \sum_{i=j-5}^{i=j+5} A_i \]
    - Accuracy \approx 2% Error
  - Amplitude ($A_i$) weighted average of frequencies ($F_i$) around the peak in spectrum to find frequency prediction ($F$)
    \[ F = \frac{\sum_{i=j-5}^{i=j+5} A_i \times F_i}{\sum_{i=j-5}^{i=j+5} A_i} \]
    - Accuracy \approx 0.05 [Hz]
Phase Determination

- Phase of FFT is not an accurate method to find phase, so alternative method required
- Cross correlation between accelerometer data and predicted acceleration wave with no phase offset
  - Find maximum correlation between data and predicted wave
- Use to find number of points \(n\) prediction lags the measurements
  - \(\theta = \frac{2\pi fn}{F_s}\)

\(f\) \(\equiv\) Frequency [Hz]
\(F_s\) \(\equiv\) Sampling Frequency [Hz]
\(\theta\) \(\equiv\) Phase Offset [rad]

Phase determined using Cross Correlation between data and predicted wave with no phase
Determination Result

- Noisy accelerometer data
  - FFT to find amplitude ($A$) and frequency ($f$)
  - Cross Correlation to find phase ($\theta$)
- Acceleration Prediction ($\ddot{x}$)
  - $\ddot{x} = A \sin(2\pi ft - \theta)$
  - Double integration of ($\ddot{x}$) to find displacement ($x$):

$$x = -\frac{A}{(2\pi f)^2} \sin(2\pi ft - \theta)$$

*Analytical Displacement* found using noisy accelerometer data
Critical Project Elements

Software

• Determination of frequency, amplitude, and phase
• Minimal computation time

Electronics

• Accelerometer calibration
• DAQ resolution and voltage range shall be appropriate to measure accelerations correlating to 1 \( \mu \text{m} \) displacements in operational frequency range
• Actuators provide 20 \( \mu \text{m} \) displacements within financial constraints
• Total error must translate to less than 4 \( \mu \text{m} \) of actuator displacement
• Vibrometer is required for verification of actuators/accelerometers
  • Must not have high pass filter
  • Must have range of \( \pm 20 \frac{\text{mm}}{\text{s}} \) velocity encoder
Critical Project Elements

Mechanical

• Flexures
  • Reduce torque on actuator tips to less than $8 \, N\cdot cm$
  • Allow for two degrees of freedom
• Modal Frequencies
  • No significant modes within operational range of 40-60 Hz
• Plates
  • Must be able to simulate rigid body
• Structure
  • Must be able to support simulated payload
Test Requirements

• Noise test:
  • FR.1 → DRT.2: Ambient noise shall not have frequency peaks which contribute more than 0.25 μm to displacement predictions
  • FR.2, FR.5 → DRT.2: SAVI testing environment shall not have greater than 1 mV of background noise

• Actuator test:
  • FR.2 → DRE-1: Electronics shall perform between 40-60 Hz
  • FR.2 → DRE-2: System shall measure and produce vibrations up to 20 μm

• Full System:
  • FR.1 → DRT.2: Cryocooler EFT’s can be imitated for testing
  • FR.3 → DRT.1, DRT.4: SAVI will support simulated camera payload
  • FR.5 → DRT.3: SAVI success is quantified by magnitude of residual vibrations relative to rigid leg

• All tests were conducted in the Mechanical Engineering MEMS lab
Locations & Naming Convention of Embedded Electronics
1. Connect accelerometers through piezoelectric charge amplifier into electronics box
2. Connect Vibrometer analog output to cDAQ NI 9205 input module
3. Accelerometers placed atop MEMS air table. Vibrometer on ground pointing at MEMS air table
4. Collect noise data at 32 kHz
5. Frequency analysis of the noise data will be done using FFT to check for peaks in operational range
6. Analysis of peak-to-peak noise amplitude of data
1. Secure test stand to vibration isolated MEMS air table
2. Attach SAVI atop test stand with SAVI solid leg above disturbance actuator
3. Align laser vibrometer with point above test actuator
   a. Follow schematic at right for vibrometer alignment depending on actuator being tested
4. Generate a 20 μm peak-to-peak disturbance in test actuator
5. Collect vibrometer and accelerometer data for motion above test actuator
6. Analyze accelerometer and vibrometer data to determine the amplitude of the actual vibration
   a) If actual loaded actuation amplitude does not match desired actuation amplitude, compute actuator sensitivity and adjust in software
7. Repeat steps 3-6 for each additional actuator
1. Secure test stand to vibration isolated MEMS air table
2. Attach SAVI atop test stand with SAVI solid leg above disturbance actuator
3. Generate simulated cryocooler disturbance with test stand at 20 μm peak-to-peak amplitude at a frequency between 40-60 Hz
4. Check disturbance amplitude and frequency with Polytec PDV100
5. Turn on SAVI system, let reach steady state
6. Check residual top plate motion with PDV100 at each of the 3 legs
7. Collect data for at least 10 seconds
8. Analyze residual tip and tilt and quantify reduction
Noise Test

- Noise level threshold set at 1 mV peak-to-peak to satisfy signal to noise ratio requirements
  - Voltage corresponds with accelerations measurements

- Vibrometer peak-to-peak noise voltage not critical because not used to operate SAVI
  - Sensitivity much greater than accelerometers
    - Voltage corresponds with velocity measurements
Noise Test Results

Peaks above ambient in frequency domain
- 13.63, 27.38, 37.26, 40.88, 43.51 Hz
- Peaks near or in operational range
  - Equivalent displacement
    \( \approx 0.0293 \, \mu m \)

Peaks above ambient in frequency domain
- Equivalent displacement \( \approx 0.000294 \, \mu m \)

Ambient noise affecting the accelerometers and vibrometer (maximum of 0.0293 \( \mu m \)) is negligible because 1 pixel of smear is caused by 0.13 \( \mu m \) displacement
Noise Test Summary

• FR.1 → DRT.2: Ambient noise shall not have frequency peaks which contribute more than 0.25 μm to displacement predictions
  • Accelerometers: Maximum peaks in operational frequency range cause at most 0.000294 μm displacement error
  • Vibrometer: Maximum peaks in operational frequency range cause at most 0.0293 μm displacement error
  • Negligible compared to measurements of 1 μm

• FR.2, FR.5 → DRT.2: SAVI testing environment shall not have greater than 1 mV of peak-to-peak background noise
  • Guarantees a high enough signal to noise ratio for accelerometers for software to function as desired
  • Peak-to-peak voltage noise is 0.493 mV
Actuator Test

- Manufacturer’s specified displacement is at no-load
  - Force applied resisting piezoelectric actuator stroke causes reduced stroke from manufacturer’s specifications
  - Higher force reduces actuator stroke
    - Test stand will experience highest gravitational loading, so lowest loaded stroke

- Loaded actuator produces smaller stroke
  - Recalibration required per test protocol

- Actuator sensitivities determined based on loaded actuation displacement measurements

<table>
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<th>Specified Stroke</th>
<th>Actual Stroke</th>
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<tr>
<td>100 V</td>
<td>100 V</td>
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<tr>
<td>No load</td>
<td>Operational load</td>
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<table>
<thead>
<tr>
<th>Test Stand Actuator</th>
<th>Specified Stroke</th>
<th>Actual Stroke</th>
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<tr>
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<td>Actuator 1</td>
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<td>Actuator 2</td>
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Actuator Test Results

- Based on measured loaded strokes of each actuator re-calibration was implemented in software to supply the appropriate voltage sensitivity
  - Per the test protocol, after re-calibration the actuator test was done again with each actuator to verify the actuator loaded stroke
- Seen right: Vibrometer velocity measurements (top) and analytical displacement (bottom)
  - 10 μm drive disturbance post calibration results in approximately 10 μm actual displacement
Actuator Testing Summary

• Requirements:
  • FR.2 $\rightarrow$ DRE-1: Electronics shall perform between 40-60 Hz
    • Actuator driven between 40-60 Hz, verifying performance
    • Calibrated actuator voltage sensitivity to yield displacements which could be accurately controlled by software
  • FR.2 $\rightarrow$ DRE-2: System shall measure and produce vibrations up to 20 $\mu$m
    • Vibrometer results after actuator calibration verify the production of 20 $\mu$m displacements
    • Accelerometers calibrated to adjust amplitude disparity to be in line with vibrometer measurements
• Accelrometer data collected for SAVI sensors at all locations
  • Ideal result:
    • Solid Leg and Residual 1 & 2 identically match
  • Actual Result:
    • Slight discrepancies in amplitude, frequency and phase of residuals from solid leg
    • Discrepancy is approximately 3 μm
    • Imperfect reduction of tip and tilt
  • Possible Measurement Errors:
    • All acceleration amplitudes empirically converted to sinusoidal displacements
• 20 μm peak-to-peak disturbance forces SAVI at a constant 50 Hz
  • Amplitude verified by vibrometer and accelerometer
Full System Test Results
Static Frequency

• Residual inertial displacements converted to relative motions to rigid leg
  • Red: Residual 1 (above SAVI actuator 1)
    • Maximum relative motion of 4 μm
    • Achieved at least 60% Reduction
  • Blue: Residual 2 (above SAVI actuator 2)
    • Maximum relative motion of 3.5 μm
• Compared to pre-mitigation, at least 60% reduction of tip and tilt attained for all time of trial
Full System Test Summary
Static Frequency

Requirements:
• FR.1 → DRT.2: Cryocooler EFT’s can be imitated for testing
  • Cryocooler EFT simulated by test stand supplying 20 \( \mu \text{m} \) disturbance at 50 Hz
  • Checked with vibrometer and accelerometers
• FR.3 → DRT.1, DRT.4: SAVI will support simulated camera payload
  • Simulated camera mass attached to SAVI for all testing of SAVI operation
• FR.5 → DRT.3: SAVI success is quantified by magnitude of residual vibrations relative to rigid leg
  • Displacement predictions indicate a 60% - 90% reduction was achieved throughout trial
Dynamic Frequency Operation

• Due to errors in phase and frequency SAVI actuators move in and out of phase from solid leg.
Steady State

Lessons Learned

• Steady State is when response is consistent between two consecutive data sets

• SAVI must recalculate 2-4 times before it can reach steady state
  • 0.5-1s to reach steady state
  • <½ of dwell time

• Steady state changes with each trial and shift in frequency
  • Errors have amplitudes of 4-10 μm
Frequency Beating

- Caused by differences in frequency from solid leg and actuating legs
- Errors gradually increase and decrease to extrema, at speeds dependent on frequency error
- Model to right
  - $\Delta f = 0.02, 0.0175$ Hz for actuators 1 and 2, respectively
  - 1.1 $\mu m/s$ shift in error
Full System Test Summary
Dynamic Frequency

Requirements:

- **FR.1 → DRT.2**: Cryocooler EFT’s can be imitated for testing
  - Cryocooler EFT simulated by test stand supplying 20 μm disturbance at varying frequencies
  - Checked with vibrometer and accelerometers

- **FR.3 → DRT.1, DRT.4**: SAVI will support simulated camera payload
  - Simulated camera mass attached to SAVI for all testing of SAVI operation

- **FR.5 → DRT.3**: SAVI success is quantified by magnitude of residual vibrations relative to rigid leg
  - Displacement predictions indicate inconsistent reduction for a dynamic frequency disturbance
Quantification of Success

Level 1:
- Pixel smear reduced by 60% to about 60 pixels of smear

Level 2:
- Pixel smear reduced by 80% so that about 30 pixels or fewer are smeared
  - 80% reduction was meet after an extended period of time in few trials
- Disturbance frequency has dwell time of 2 seconds and reduction meets Level 1
  - Reduction of tip and tilt does not always meet Level 1

Level 3:
- The system dimensions will not exceed 20 cm x 20 cm x 10 cm
- The system mass will not exceed 5 kg
- The system will use no more than 10 W of power
  - Power draw of electronics exceeds 10 W (excluding computer)
Systems Engineering

• Systems engineering approach closely follows the SE V-diagram
• Spans from project definition meetings and research to validation and verification of the full system
• Emphasis on requirements flow-down and methods to verify and validate subsystems and full system
Systems Engineering Approach

- **Project Definition: PDD**
- **FBD, CONOPS, CDD**
- **Requirements Flow down**
- **High Level Design: PDR**
- **Detailed Design: CDR**
- **System validates CONOPS**
- **SAVI verified by requirements**
- **SAVI Validation**
- **SAVI Verification**
- **Actuator Subsystem V & V**
- **Electronics Calibration**
- **Manufacture/Purchase Hardware, Develop Software, Integration**

**Changes and upgrades not able to be made due to lack of time**

- **Several iterations to reach final project definition**
- **Design Concept Trade Studies**
- **High Level Trade Studies**

**Timeline:**
- **Fall 2013:** Decomposition and Concept Development
- **Spring 2014:** Verification and Validation

**Key Steps:**
- **Fall 2013:**
  - Project Purpose
  - Design Description
  - Test Overview

- **Spring 2014:**
  - Test Results
  - Systems Engineering
  - Project Management
Systems Engineering Issues

• Developing a well defined problem
• Designing flexures that would allow proper movement of top plate without damaging the actuators
• Limited time with vibrometer constrained testing schedule
• Limited quality of electronics due to financial budget
Lessons Learned

• The mechanical system cannot handle robustness
  • Possibility of modal resonance affects alternate configurations
• Having a well defined problem with proper requirements and levels of success is important before moving on to choosing a design solution
• Fulfilling functional requirements should be completed before starting additional analysis
• Should have consulted with experts more frequently
• Quality of hardware is extremely important to micron vibrations
• Many unforeseen phenomenon can derail the project operation
Project Management

• Traditional Approach
  • Initiating
  • Planning
  • Executing
  • Monitoring/Controlling
  • Closing
Initiation & Planning

Initiation

• Development of problem statement
• Organizational Chart
• Work Breakdown Structure
• Development of requirements flow down

Planning

• Gantt chart development
• Status meetings
  • 2-3 times per week with all in attendance
• Weekly advisor meetings with Dr. Rakow
• Technical meetings
  • At the discretion of Technical Leads
Executing, Monitoring, and Controlling

Executing
• Project Manager
  • Coordinated Technical Leads to complete technical tasks according to the schedule
• Team Leads
  • Coordinated people to carry out technical tasks
  • Chose times to carry out joint tasks

Monitoring and Controlling
• Scope Management
  • Team member skills
  • Time and budget constraints
• Monitor success of requirements
• Corrective action for objectives not met
Successes and Difficulties

Successes
• Met overall budget and schedule constraints
• Few risk off-ramps were taken
• Successful team dynamic
• Communication methods
• Safety measures followed

Difficulties
• Multiple redefinitions of problem statement caused schedule slip
• Constant change in scope throughout both semesters
# Budget Comparison

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*This item was borrowed*
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BUDGET BREAK DOWN

- Electrical: 12%
- Mechanical: 59%
- Miscellaneous: 21%
- Remaining: 8%
Corporate Cost

- On average group members spent about 16 hours per week
- For 8 members over 32 weeks this comes to about 4096 hours
- This comes to about $256,000 (excluding material costs)
Backup Slides
Modal Resonance?

• There should be a single peak at 50 Hz

FFT of voltage data shows build up of peaks within 10% of actuation frequency, indicating possible resonance
Continued Research?

• Occurs in second configuration
  • 120° rotation of SAVI from first configuration (disturbance actuation under actuator 2)
  • Second Configuration is more mechanically complex than first, making modal analysis a three dimensional problem, thus outside the scope of this project

• If time allowed, additional testing for robustness required
  • Frequency sweeping to empirically find modes