Control of the UltraLITE Precision Deployable Test Article Using Adaptive Spatio-Temporal Filtering Based Control

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Overview

- UltraLITE Deployable Optical Telescope program
- DOT test beds
  - Mirror Mass Simulator
  - PDOS
  - DOT BGD
- Active structural control issues
- Spatio-Temporal Filtering (STF)
- STF based structural control
- PDOS test experience
• Phase II SBIR award from Ballistic Missile Defense Organization (BMDO)
• Contract managed by and technical collaboration with Air Force Research Lab - Kirtland AFB
- Large aperture/resolution through deployable, sparse, optical array
- Deployable primary mirrors
- Golay 6 configuration
- Telescoping secondary tower
• Mirror Mass Simulator (MMS)
• Precision Deployable Optics Structure (PDOS)
• Deployable Optical Telescope Brassboard Ground Demonstration (BGD)
Preliminary DOT Evaluation - Mirror Mass Simulator

- Mirror Mass Simulator mounted to optics bench
- 3 interferometer displacement sensors
- 3 piezo stack actuators
- Electromagnetic disturbance shaker
Precision Deployable Optical Structure

- Actuation Subsystem
- Optical Subsystem & Truth Sensor
- Mirror Simulator
- Deployable Boom
- Interface
- Granite Slab
Deployable Optical Telescope
Brassboard Ground Demonstration

Integrated Technology in Simulated Space/Ops Environment
Supporting SBL, Global Virtual Presence, and Tactical Imaging Missions
Requirements

SDL’s primary mission is to provide a Vibration Control System that will assist the Optical Control System in meeting the DOT mirror positioning requirements

- **Precision Deployable Optical Structure (PDOS):**
  Achieve 30 nanometers or less RMS value for relative displacement between the granite slab and the mirror mass simulator

- **Deployable Optical Telescope (DOT)**

  1. Maintain the position of the primary mirror segments within:
     - Piston: ± 14 nanometers error per segment
     - Tilt: ± 95 nanoradians error per segment

  2. Maintain the position of the secondary mirror within:
     - Decenter: ± 50 microns
     - Piston: ± 4 microns
     - Tilt: ± 20 microradians
Deployable Optics - Jitter Requirements

- Disturbances
  - torque wheel actuators
  - slewing
  - space based laser

- Vibration Control
  - isolation
  - passive vibration control
  - high bandwidth position control
  - active vibration control
Active Structural Vibration Control Issues

- **Modeling** - accurate and complete dynamic models of complex “real-world” systems are difficult to obtain.
- **Time Variance** - Often, by the time you’ve got the model the system has changed - It’s a moving target.
  - System dynamics - temperature, load, wear, damage
  - Discrete failures - sensors, actuators, signal conditioning
- **Computational burden**
Spatio-Temporal Filter Based Control

Uncontrolled Response

Uncontrolled Modal Responses Extracted with STF

Controlled Modal Responses

Controlled Response
Modal Coordinate Transformation
Uncouples System into SDOF Modes

\[ M\ddot{x} + C\dot{x} + Kx = f \]

\[
\begin{bmatrix}
\ddots \\

m & \ddots \\

\vdots & \ddots & \ddots \\

\end{bmatrix}
\begin{bmatrix}
\ddots \\

\ddots & c \\

k & \ddots \\

\end{bmatrix}
\begin{bmatrix}
\ddots \\

\eta \dot{} \\

\eta \\

\end{bmatrix}
= \Phi^T f
\]

\[ x(t) = \sum_{r=1}^{N} \phi_r \eta_r(t) = \Phi \eta(t) \]
STF Origin - Modal or Spatial Filtering

Spatial filter vector $\Psi$

$$\psi_i^T \phi_r = 0 \quad i \neq r$$

$$= 1 \quad i = r$$

$$\psi_i^T x(t) = \psi_i^T \sum_{r=1}^{N} [\phi_r \eta_r(t)]$$

$$= \psi_i^T \phi_i \eta_i(t)$$

$$= \eta_i(t)$$

Extract single mode response from measured response
Spatio-Temporal Filtering

Spatial filter estimate of $\eta$ at time $k$

$$\hat{\eta}_k = \psi^T x_k$$

Spatio-Temporal filter estimate of $\eta$ at time $k$

$$\hat{\eta}_k = \psi^T \begin{pmatrix} x_k \\ x_{k-1} \\ \vdots \\ x_{k-Nt} \end{pmatrix}$$
• FIR or “all-zero” filter on each channel
• Pole-zero cancellation & preferential pass filter
  – fewer sensors required
• Inherent estimation of modal velocity
• Compensation for filter delays, sensor & signal conditioning dynamics
• Non-homogeneous sensor suites - piezo patches, accelerometers, etc.
• Know only poles of controlled modes
• Don’t know
  – mode shapes
  – modal scaling factors (modal mass)
  – modal participation vectors
  – anything about uncontrolled modes (not even poles)
Adaptive Calculation of STF Coefficients using Reference Model Approach

**SDL**

SDOF (Single Mode) Reference Model

\[ \eta_{k+1}^{(r)} = z_{\lambda} \eta_{k}^{(r)} + l^T f_k \]

\[ \eta_{k+1}^{(r1)} = z_{\lambda} \eta_{k}^{(r1)} + f_k^{(1)} \]

\[ \vdots \]

\[ \eta_{k+1}^{(rN_i)} = z_{\lambda} \eta_{k}^{(rN_i)} + f_k^{(N_i)} \]

\[ \eta_{k}^{(r)} = l^T \begin{bmatrix} \eta_{k}^{(r1)} \\ \vdots \\ \eta_{k}^{(rN_i)} \end{bmatrix} + \eta_{k}^{r} = l^T \eta_k^{r} \]
Adaptive Calculation of STF Coefficients using Reference Model Approach

\[ e_k = \eta_k^{(r)} - \hat{\eta}_k \]

\[ = l^T \eta_k^r - \psi^T \begin{bmatrix} x_k \\ x_{k-1} \\ \vdots \\ x_{k-Nto} \end{bmatrix} = \begin{bmatrix} \psi^T \\ l \end{bmatrix} \begin{bmatrix} -x_k \\ \vdots \\ -x_{k-Nto} \\ \eta_k^r \end{bmatrix} \]
STF Based Modal Velocity Feedback Control

Control Command Vector for $i$'th mode

$$f_c^{(i)} = \hat{\eta}^{(i)} \alpha^{(i)} v^{(i)}$$

Modal Coordinate Velocity Estimate

Force Vector

Scalar Feedback Gain

Estimated Modal Participation Vector is Ideal Force Vector
Initial Mirror Mass Simulator Control Experiments

- STF based velocity feedback
- 3 inputs, 3 outputs, 5 controlled modes
- Random disturbance excitation
- 1 1/2 days to implement
  - familiarization with test bed
  - all system ID
  - control implementation and testing
Implementation of STF Based Control
Preliminary DOT Evaluation - Mirror Mass Simulator

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Interferometer 1 versus Disturbance Force

Amplitude - Displacement/Force vs Frequency - Hertz
Interferometer 2 versus Disturbance Force

Amplitude – Displacement/Force

Frequency - Hertz
Interferometer 3 versus Disturbance Force

Frequency - Hertz

Amplitude - Displacement/Force
Precision Deployable Optical Structure

- Back-Up Structure
- Gravity Off-Load
- Mirror Inertial Simulator
- Reference Bench
- Composite Boom

Proved Deployment, Acquisition, Maintenance and Control System for a 2m Optical Segment
Precision Deployable Optical Structure
Interferometer 1 / PZT 2 FRF

- 5 Hertz boom mode only mode in low frequency range
- 1.6 Hertz slab mode not apparent - must treat as a disturbance
STF Control
PDOS 5 Hz Boom Mode
Open and Closed Loop Interferometer PSD’s

![Graph of Open and Closed Loop Interferometer PSD’s](image)
• RMS Vibration, 0-250 Hz
  • Int 1: 171-430 nm
  • Int 2: 117-264 nm
  • Int 2: 93-239 nm
• Resonant and forced vibration
Interferometer RMS Value Versus Frequency Band

![Graph showing Interferometer RMS Value vs Frequency Band](image)
• RMS Vibration, 0-250 Hz
• Assuming 50x reduction 0-13 Hz.
  • Int 1: 29.99 nm
  • Int 2: 28.51 nm
  • Int 3: 27.42 nm

• Note the control objective is 30 nm RMS vibration levels
Conclusions

- Resonant control alone is not sufficient to meet PDOS/DOT optical jitter control requirements
- “High” bandwidth position control in conjunction with resonant mode control required
- STF based modal control is practical approach for resonant mode control;
  - Implement effective MIMO control on complex, “real-world” structures with little knowledge of dynamics
  - Adapts to sensor/actuator failure
  - Accommodates filter/signal conditioning dynamics
  - Easily updated to accommodate changing system dynamics (only update poles of controlled modes)