Closed Loop Electrostatic Actuation of Membrane Mirrors

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Outline

Introduction

Area Control
  Single Mode Actuation
  Multiple Mode Actuation

Gap Control

Conclusion
Membrane Mirror Actuation (Not an SBIR/STTR Project)

**Innovation**

- Development of a dynamically controlled actuation system for membrane mirrors

**Accomplishments**

- Low-moderate voltage, large deflection, large-force electrostatic actuation
- Variable-area, variable-gap techniques developed
- Closed loop, current bandwidth $\rightarrow 500$ Hz.

**Government/Science Applications**

- Laser and microwave communication
- Nonlinear control with optics feedback
Background

- Large deformable reflectors
  - large actuation authority desirable (i.e., large forces and/or deflections)
- Membrane reflectors (monolithic, conformable, deployable)
  - slow natural response vs. need for greater bandwidths
    - aberration corrections (atmospheric turbulence, slewing dynamics–structural coupling)
    - process requirement (e.g., communication)
- Electrostatic actuation well suited for force and deflection authority requirement
Introduction

- Voltage difference between 2 conductors causes force

\[ F = \frac{\varepsilon V_a^2 A}{2 G_0^3 (1 - X)^2}; \quad \left( X = \frac{x}{G_0} \right) \]  

(1)

where \( V_a \) is the voltage across the electrode, \( A \) is the area of the active electrode, and \( \varepsilon \) is the permittivity, here, of air.

- Active electrode on fixed substrate, metallized membrane provides the neutral electrode
Membrane Actuation

To produce deflection $w(r, \theta; t)$ at any point, apply force $f(r, \theta; t)$. The force distribution over the membrane could be controlled in real time by controlling:

- voltage on the active electrodes
- area of the active electrodes
- gap between the individual active electrodes and membrane

![Diagram of Membrane Actuation](image)
Membrane Actuation (II)

- Voltage control
  - commonly used and intuitive
  - high voltages for large deflections
  - closed-loop control requires accurate manipulation of large voltages

- Area control
  - Segmented active electrodes
  - switching on/off segments to control active area
  - constant voltage
  - closed-loop control now a switching problem

- Gap Control
  - multiple aberration modes using a single control input
  - actuate substrate mechanically; constant voltage, constant area control
  - continuous control
Mirror Actuation for Large Deflection

- Voltage control methods: Zhu et al. (2007), Maithripal et al. (2006), Seeger et al. (2004); closed loop control necessary for deflections $> \frac{1}{3}$ gap size.
- Area control and gap control: results discussed here
- Results published in Korde (2008, 2009, 2010)\textsuperscript{1}

\textsuperscript{1}J. Intelligent Material Systems and Structures, v. 21, January 2010, pp. 61-82
J. Intelligent Material Systems and Structures, v. 19, n. 11, pp. 1339-1359
Single Mode Control

- Deflection range at mirror center $\rightarrow$ full gap size $G_0$ (40 $\mu$m here),
- Tip/tilt deflection $\rightarrow$ maximum allowed by $G_0$ (3 mrad here),
- Response bandwidth of 500 Hz.
Single Mode Control (II)

- **Dynamics (Lumped Parameter Model)**

\[
\dot{X}_e = V_e \\
\dot{V}_e = -KX_e - DV_e + \frac{\varepsilon V_a^2}{2G_0^2(1 - X_e)^2 m_e} A(t) \tag{2}
\]

- **Nonlinear system**
- **Mass** \(m_e\), **stiffness** \(K\) and **damping** \(D\) from energy considerations
Single Mode Control (III)

Mirror for single-mode 2-way actuation
Single Mode Control (IV)

- Specify reference trajectory for mirror deflection for focus/defocus or tip/tilt beam deflection
- Compute corresponding reference area variation and discretize to minimum segment area
- Dynamic observer design based on quad cell input
- Lyapunov potential method for variable gain controller design for trajectory tracking
Single Mode Control Results (I)

Simulation results: discrete area control with observer feedback
Single Mode Control Results (II)

Experimental results: discrete area control with observer driven by quad-cell measurements
Multiple Mode Actuation (I)

- Up to 12 aberration modes
- Bandwidth of 500 Hz
- Center deflection $\pm 100 \mu m$
- Electrostatic actuators placed along boundary
- Mirror surface metallic
- Closed loop control
- Possible with area control or gap control
Multiple Mode Actuation (II)

Mirror design

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Closed Loop Actuation
Multiple Mode Actuation (III)

Mirror actuator clusters for variable area control
Multiple Mode Actuation (IV)

Completed mirror undergoing static tests
Multiple Mode Actuation (V)

Excitation with 260 V (Left) and 280 V (Right)
Gap Control: Basic Features

- Mechanical or piezoelectric control of electrode gap
- Single control variable for multiple-mode actuation
- Constant voltage on constant-area electrodes
- Potentially large number of aberration modes
- Switch on/off selected actuators to determine aberration modes corrected for
Gap Control Schematic

Substrate is driven mechanically/piezoelectrically; single control variable $x_s(t)$.
Gap Control Goals

- Bandwidth of 500 Hz.
- Target deflection 60 µm
- Trajectory tracking in the presence of random measurement error and random platform vibration
Dynamic Formulation

Nondimensionalized equations of motion

\[ \dot{x} = v \]

\[ \dot{v} = -2\zeta\omega_0 v - \omega_0^2 x + \frac{1}{3}q^2\omega_0^2 + u \]

\[ \dot{q} = \frac{1}{R_p C_0} \left( -q(1 - x) + \frac{2}{3}V \right) \]  \hspace{1cm} (3)

\( u \) is the control variable given by

\[ -G_0 u \equiv -\ddot{x}_s - \frac{b}{m_e} \dot{x}_s - \frac{k_e}{m_e} x_s \]  \hspace{1cm} (4)

where \( x_s \) denotes the displacement through which the substrate is driven.
Control Approach

- Reference trajectory for mirror corresponding to deflection and bandwidth
- Corresponding reference trajectory for gap variation
- Closed loop control to keep actual motion on reference trajectory
- Dynamic observer
- Lyapunov potential method
- Controller design to ensure velocity errors $\to 0$ in the presence of measurement error and platform vibration.
- Measurement error and platform vibration assumed to be 1st order Markov processes
Control against measurement error and platform vibration

- Errors in sensor measurements used in feedback
- Taken to be random but band-limited; 1st order Markov process
- Platform (e.g. air/space vehicle) where mirror is mounted subject to vibration
- Taken to be band-limited; also 1st order Markov process
Gap control results

Simulation results; Close trajectory tracking with closed loop control based on dynamic observer estimates; random measurement error and platform vibration

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Closed Loop Actuation
Gap Control: Measurements

Static measurements

Static tests; surface measurements on the boundary-actuated mirror using a laser displacement sensor.
Gap Control: open loop static measurements

$G_0 = 69 \mu m$ (Left) and $G_0 = 129 \mu m$ (Right)

Open loop static tests; all actuators on (at 500 V); focus/defocus mode.
Conclusion

- Two methods examined for electrostatic control of membrane reflectors
  - Area Control
    - closed loop control a switching problem
    - precise control seen in simulations
    - oscillations seen in experimental results
  - Gap Control
    - continuous control
    - precise control in presence of measurement error and platform vibration
    - concept shown to work in static open loop tests
    - dynamics experiments underway
- Bandwidth, deflection requirements met in both cases
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