Sensor and Actuator Technology Development

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Outline

- Sensor and Actuator Placement for Robustness
- Self-Sensing Actuators
- Nonlinear Actuation Models
Sensor/Actuator Selection

- Sensor and actuator selection/placement sets an \textit{a priori} limit on closed loop performance.

- Correct placement can improve nominal performance for any specific control design technique.

- Placement problem has been investigated previously
  - open loop vs. closed loop algorithms
  - optimal vs. heuristic algorithms

- Degrees of freedom for sensor and actuator suite design:
  - Number
  - Type
  - Location
  - subject to design constraints

- Placement is typically done using initial inaccurate model.
Sensor/Actuator Selection for Robustness

- **Concept:** Select sensors and actuators to minimize impact of model inaccuracies on achievable performance and stability.

- **Motivation:**
  - Placement and resulting closed-loop performance/stability are a strong function of model.
  - Only have uncertain model on which to base placement decisions.
  - Implies large uncertainties in achievable closed-loop performance or robustness.

- **Method:** Incorporate model uncertainty information into open or closed loop placement algorithms.
Achievable Performance Robustness

- Control design must use actuator and sensors it is given.
  - Example: Loss of controllability when actuator is unwittingly placed at a node.
- Can enable control task by introducing performance robustness through s/a set.
Representing the Uncertain System

- All system matrices affected by model uncertainty
- Focus on finite element errors, not ID errors
- Determine eigenvector uncertainty to expected errors:
  - Stiffness of components
  - Boundary conditions
  - Mass distribution
- Two approaches:
  - Range of possible plants/systems over all uncertain parameters
  - Sensitivity of nominal plant/system to uncertain parameters
**Figures of Merit**

- Open loop analysis of sensor/actuator options used to reduce number of choices to manageable number

- Use controllability and observability gramians

\[ W_c(t_0,t_1) = \int_{t_0}^{t_1} \phi(t_1, \tau) B(\tau) \phi^T(t_1, \tau) d\tau \]

- Calculate with Lyapunov equation for each value of uncertainty

\[ 0 = A_i W_{c_i} + W_{c_i} A_i^T + B_i \sum_{w} B_i^T \]

- Closed loop cost

\[ J_{cl} = tr\{Q C_i^T C_i\} \]

where

\[ 0 = A_i Q_i + Q_i A_i^T + B_i B_i^T \]
Design Algorithms

- Open loop
  - Compute expected value of gramians over entire uncertainty set
  - Reduce number of s/a options by straight ranking

- Closed loop
  - Use existing techniques for optimization
  - Cost is expected value over uncertainty set

- Trade off degree of open loop reduction vs. size of set for closed loop optimization
Current Efforts

- Analytical sample problem: cantilevered beam
  - 6 sensors, 6 actuators
  - LQG control (SISO and TITO)

- Interferometer testbed
  - Analysis based on finite element model
  - Uncertainty description provided from system ID data
  - Main focus is active strut placement problem
  - Experimental demonstration of improved closed loop performance based on sensor/actuator location and type
Piezoelectric Actuation and Sensing

- Structure with piezoelectric actuators/sensors.

- Governing Equations of Motion:

  \[ (M_s + M_p)\ddot{r} + (K_s + K_p)r - \Theta v = B_f f \quad \text{Actuator Eq.} \]

  \[ \Theta^T r + C_p v = B_q q \quad \text{Sensor Eq.} \]
Simultaneous Sensing and Actuation

- **Concept**: Use the same piece of piezoelectric simultaneously as both a structural sensor and an actuator.

- **Motivation**:
  - Eliminates need for separate sensor. Reduced signal conditioning.
  - Perfectly collocated dual sensor useful for structural control.

- **Modelling**: If the applied current and piezoelectric electrode voltage is known, one can reconstruct the mechanical strain or strain rate.

\[
\Theta^T r = q - C_p v \quad \Theta^T \dot{r} = i - C_p \dot{v}
\]

- The \( \Theta^T r \) term is proportional to averaged strain state as for the charge based sensor.

\[
\Theta^T r = \int_{V_p} \left[ e_{31} S_1 + e_{31} S_2 + e_{33} S_3 \right] dv
\]

- More insight can be gained on the physical significance of the terms by using a piezoelectric circuit analogy.
Physical Interpretation

- The piezoelectric transformer analogy is useful for determining the physical significance of the terms. The piezoelectric element is represented as a transformer converting mechanical energy to electrical and vice versa.

![Diagram of piezoelectric transformer analogy]

- The sensor equation can be interpreted physically as measuring the difference in between applied current and the capacitance current.

\[ \Theta^T \dot{\mathbf{r}} = \mathbf{i} - C_p \dot{\mathbf{v}} \]

\[ \mathbf{i} = i_{\text{mech}} - i_{\text{tot}} + i_{\text{elec}} \]
**Simple Circuit Implementation**

- **Strain Rate Circuit**

![Circuit Diagram]

- Also possible to implement simple strain sensing circuit by measuring applied charge rather than current.
System for Experimental Demonstration

- Cantilevered beam with PZT wafers on the surface.
Open Loop Results

- Model compares well with measurement
- Zero location matching hindered by PZT hysteresis
**Closed Loop Results**

- Tip displacement/force input with "sensuator" loop closed

![Closed Loop with PPF Filter](image1)

- Positive position feedback (PPF)

![Closed Loop with LQG Controller](image2)

- LQG

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Applications

• Retrofit of sensing capability on existing actuator systems
  - Information on local deformation
  - Information for collocated control (addition of damping)
• Linearization of actuator response
• Health monitoring and system identification
• Active structural control (high gain collocated loops)
Nonlinear Actuation Models

- **Concept:** Develop models of actuated structures capable of handling actuation material nonlinearities

- **Motivation:**
  - Piezoelectric material properties are nonlinear at high strains.
  - Higher actuation performance available from inherently nonlinear materials.
    - Electrostrictive materials
    - New high-strain, shape-memory ceramics.

- **Approach:**
  - Microscopic material models for capturing relevant physics.
  - Macroscopic phenomenological models for nonlinear structural response using energy methods.
Conclusions

- Ongoing work in three areas:
  - Robust Actuator and Sensor Placement
  - Self-Sensing Actuation
  - Nonlinear Actuation Modeling

- Robust actuator and sensor placement addresses a clear need but faces the difficulty of good error model development.

- Self-sensing actuation has been demonstrated and modeled, works well in active control systems for simple structures, and is being applied to built up structures.

- New research on nonlinear actuation models holds promise for high fidelity modeling of high strain actuation materials.