MIT
Space
Engineering
Research
Center

Sensor and Actuator Technology Development

Eric Anderson and Nesbitt W. Hagood

January 23, 1992

Outline

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

Sensor/Actuator Selection

- Sensor and actuator selection/placement sets an *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 — subject to design constraints
  Location

- Placement is typically done using initial inaccurate model.

Sensor/Actuator Selection for Robustness

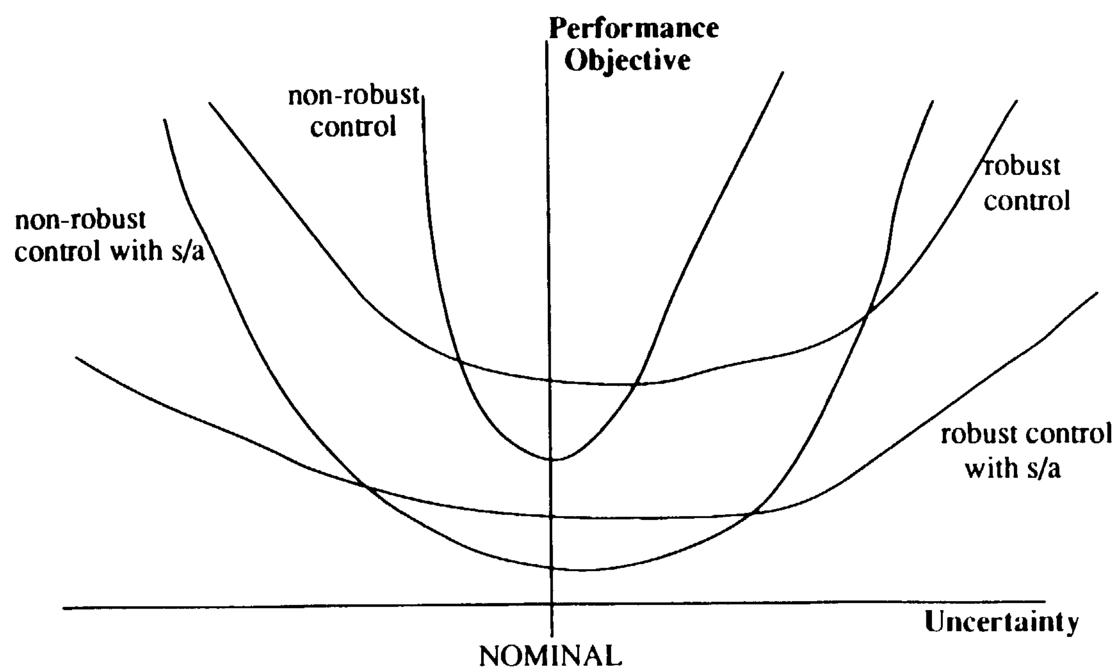
- Concept: Select sensors and actuators to minimize impact of model inaccuracies on achievable performance and stability.

- Motivation:
  - Placement and 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

$$0=A_iW_{c_i}+W_{c_i}A_i^T+B_i\sum\nolimits_{ww}B_i^T;$$

- Closed loop cost

$$J_{cl}=tr\left\{\left\langle QC_i^TC_i\right\rangle\right\}$$

where

$$0=A_iQ_i+Q_iA_i^T+B_iB_i^T$$

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

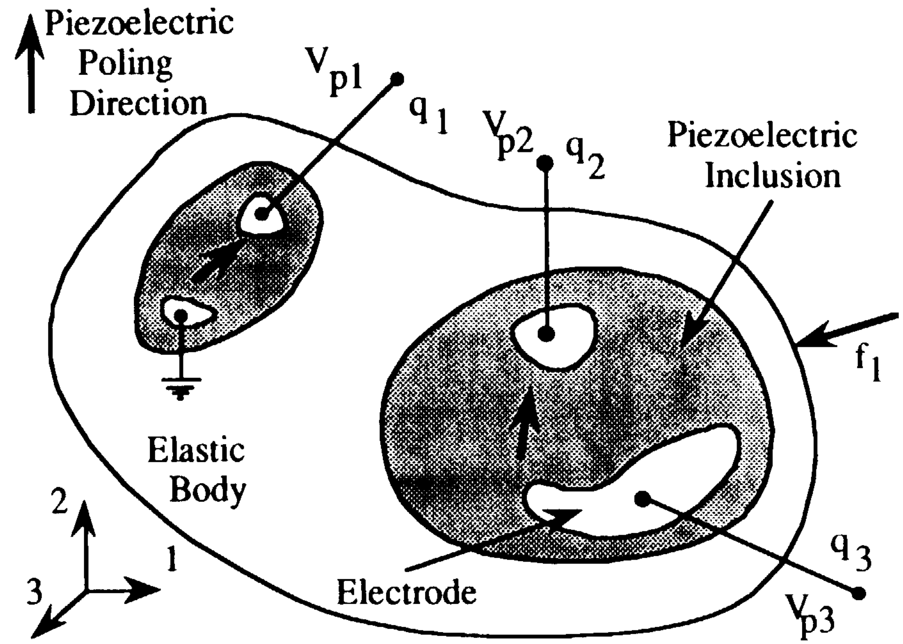
Current Efforts

- 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:

$$\left(\mathbf{M}_s+\mathbf{M}_p\right)\ddot{\mathbf{r}}+\left(\mathbf{K}_s+\mathbf{K}_p\right)\mathbf{r}-\Theta\mathbf{v}=\mathbf{B}_f\mathbf{f} \quad \textit{Actuator Eq.}$$

$$\Theta^T\mathbf{r}+\mathbf{C}_p\mathbf{v}=\mathbf{B}_q\mathbf{q} \quad \textit{Sensor Eq.}$$

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.

$$\boldsymbol{\Theta}^T \mathbf{r} = \mathbf{q} - \mathbf{C}_p \mathbf{v} \qquad \boldsymbol{\Theta}^T \dot{\mathbf{r}} = \mathbf{i} - \mathbf{C}_p \dot{\mathbf{v}}$$

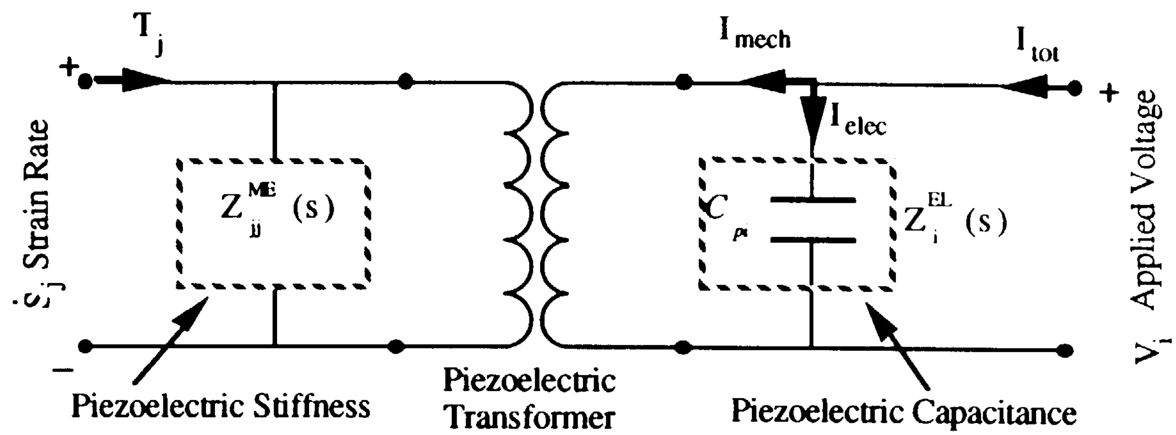
- The $\Theta^T r$ term is proportional to averaged strain state as for the charge based sensor.

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

- 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.

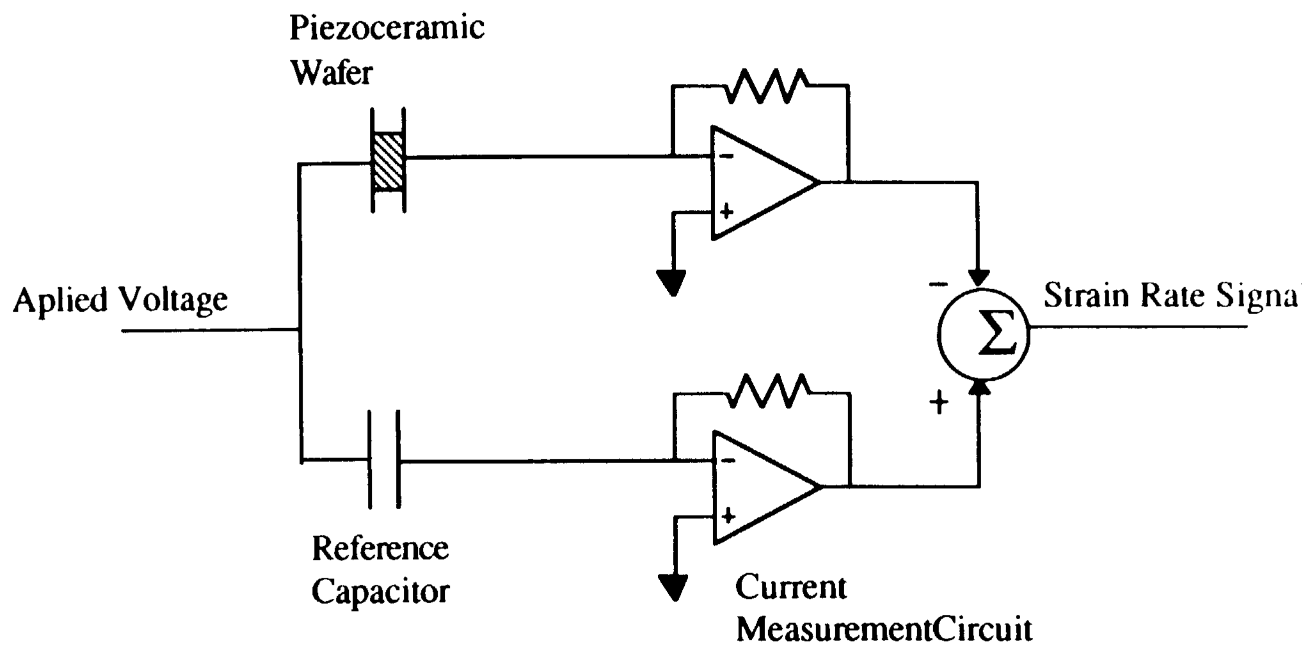


- The sensor equation can be interpreted physically as measuring the difference in between applied current and the capacitance current.

$$\underbrace{\mathbf{\Theta}^T\dot{\mathbf{r}}}_{i_{mech}} = \underbrace{\mathbf{i}}_{i_{tot}} - \underbrace{\mathbf{C}_p\dot{\mathbf{v}}}_{i_{elec}}$$

Simple Circuit Implementation

- Strain Rate Circuit

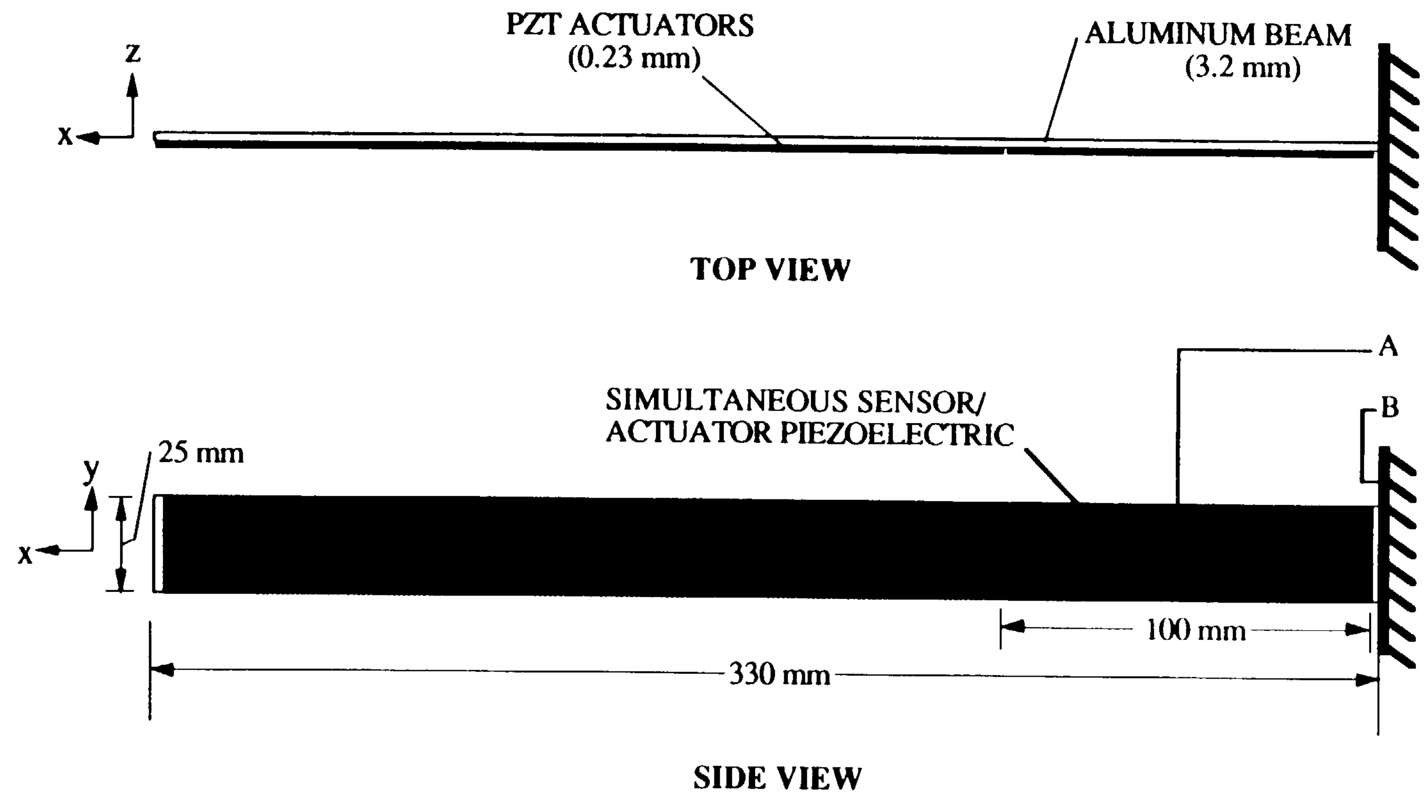


B) Strain-Rate Sensing Configuration

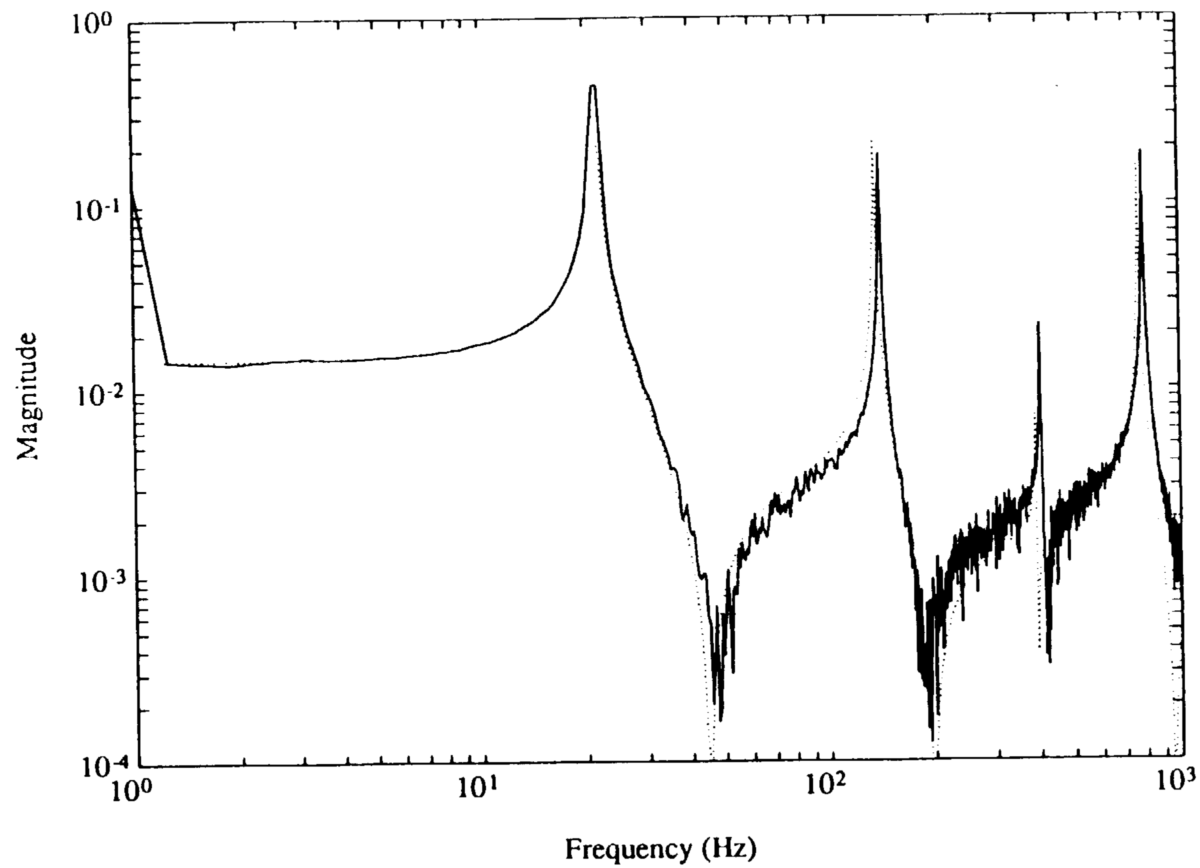
- Also possible to implement simple strain sensing circuit by measuring applied charge rather than current.

System for Experimental Demonstration

- Cantilevered beam with PZT wafers on the surface.



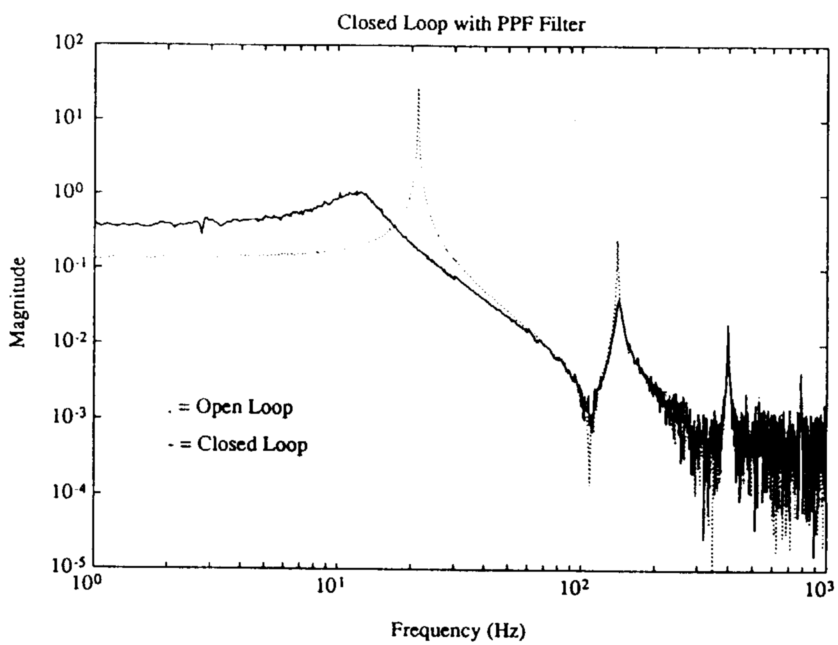
Open Loop Results

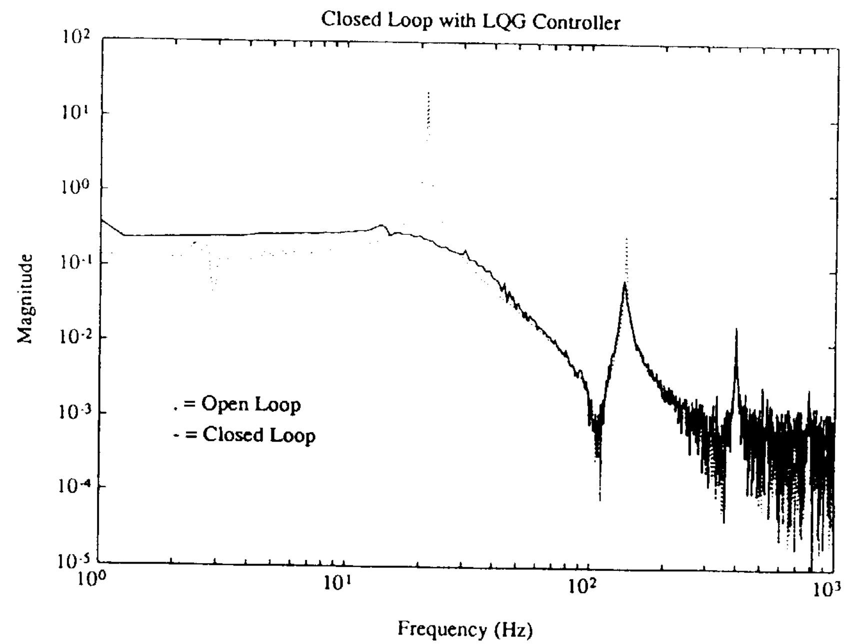


- Model compares well with measurement
- Zero location matching hindered by PZT hysteresis

Closed Loop Results

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





- Positive position feedback (PPF)
- LQG

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.