Control of Micro Mirrors for High Precision Performance

Jessica R. Bronson, Gloria J. Wiens
University of Florida
231 MAE-A, P.O. Box 116250
Gainesville, FL 32611-6250
1-352-392-0806
jraeb@ufl.edu, gwiens@ufl.edu

ABSTRACT
Microelectromechanical Systems (MEMS) technology has already led to advances in optical imaging, scanning, communications and adaptive applications. Many of these efforts have been approached without the use of feedback control techniques that are common in macro-scale operations to ensure repeatable and precise performance. This paper examines control techniques and related issues of precision performance as applied to a one-degree-of-freedom electrostatic MEMS micro mirror.

Keywords
MEMS, electrostatic, micro mirror, feedback control

1. INTRODUCTION
Micromirror arrays are one of the most successful and versatile MEMS innovation with applications including optical switches for telecommunications, scanning and imaging for projection displays, diffraction gratings for optical spectroscopy, and adaptive optics for wave front correction in telescopes [1-11]. Some of these applications require high precision positioning capabilities that cannot be achieved through open-loop control alone. Furthermore, many of the devices require large arrays of micromirrors where it is desirable to ensure accurate positioning capabilities for each mirror in the array despite the presence of outside disturbances or variations from the fabrication process such as small deviations in dimensional or material properties across the array. While open-loop control has been used successfully in mirror arrays for on/off binary-actuation, many of today's emerging technologies require analog positioning capabilities. In order to guarantee precision and accuracy of the mirror position for analog operation, feedback control techniques are required. Feedback control has long been used in many macro-scale systems to correct for such factors, yet limited work has been done to apply these techniques to MEMS systems.

This paper will examine the modeling of the actuator dynamics and investigate feedback control methodologies that can be used to achieve high precision positioning. The development of such control strategies will contribute to the advancement of many precision optical applications.

1.1 Microelectromechanical Systems
MEMS devices and components have feature sizes ranging from 1 μm to 1 mm and are batch fabricated using a microfabrication process such as surface micromachining [12]. Surface micromachining creates structures by layering a structural layer, such as polysilicon, with a sacrificial layer, such as silicon dioxide (oxide). Through a repeated series of lithography, etching and deposition, free-standing structures are created. The process utilized to create the device discussed here is Sandia National Laboratories SUMMiT V that utilizes five layers of polysilicon [13]. The names and thickness of each layer are show in Figure 1. Sacrificial oxide is used in between the polysilicon layers to create the layered structures.

1.2 1-DOF Micro Mirror
Many micromirror actuators are electrostatically actuated and exhibit the well-documented phenomenon of electrostatic pull-in. Many of the first generation of micromirror devices, such as Texas Instruments' Digital Micromirror Device (DMD), use pull-in as an advantage that allows for on/off binary actuation at reduced voltages [9]. While the actual pull-in voltage of the device may vary slightly from mirror to mirror due to variations in dimension and material properties, reliable open-loop operation can still be guaranteed by ensuring that the actuation voltage is sufficiently high enough to capture the pull-in effects for all the mirrors despite these variations. In order to move beyond binary positioning capabilities and achieve full, analog positioning for applications such as scanning and adaptive optics, feedback control techniques that are commonly used in macro world applications must be applied to MEMS devices.

Feedback control can help to increase the stable region of operation, provide accurate and precise positioning that is robust with respect to variations in device fabrication, and also reject outside disturbances such as vibrations and other noise sources.

Like many electrostatically actuated devices, the micromirror presented here exhibits nonlinear behaviors such as pull-in instability. These nonlinearities are a common problem that is generally undesirable for analog mirror designs. However the presence of nonlinear behavior in these designs further enriches the complexity of the device and offers opportunities to explore advanced control methods for nonlinear systems.

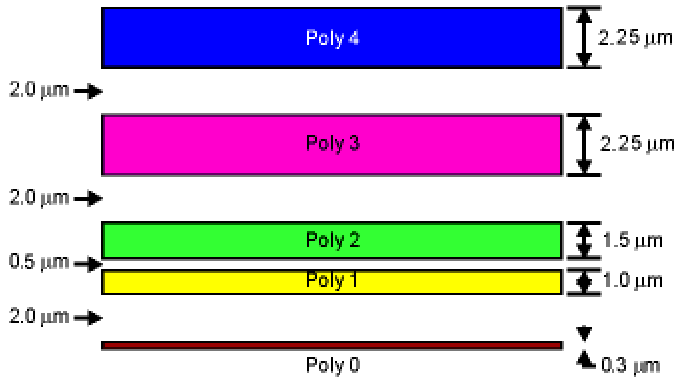

Figure 1. Layer thickness of SUMMiT V polysilicon [13].

The device presented in this paper is a one-degree of freedom micro mirror actuated via a vertical comb drive and is shown schematically in Figure 2. The mirrors are fabricated in polysilicon by surface micromachining and are actuated with electrostatic vertical comb drives located beneath the mirror surface. This allows for large arrays with high fill factors. Vertical comb drives are more easily controlled than parallel plate actuators, making them a good choice for analog scanning devices [1-5,10].

The physical nature of electrostatic actuation introduces highly nonlinear behavior into the actuator function and results in a well-documented instability known as pull-in. Many researchers have sought ways to model and to alleviate this instability including the use of mechanical design alterations [14,15] and by using feedback control [16]. In addition to stabilizing the actuator across the instability point and extending the range of travel, the implementation of control techniques can also be used to control position of a single mirror. For mirrors in a large array, it can ensure uniform operation of mirrors throughout the array and alleviate the effects of uncertainties from fabrication errors in surface micromachining [17] and reject outside disturbances [18].

This paper will first examine the dynamic model of the micro mirror device and discuss the nonlinear behaviors that arise from electrostatic actuation. Possible control strategies that can be applied to this problem are then presented followed by a brief discussion regarding the related issue of sensor development for the physical implementation of feedback control.

2. ACTUATOR DYNAMICS

One limiting factor to most electrostatic actuators is the electrostatic pull-in instability that occurs when the electrostatic force overcomes the mechanical restoring force. When pull-in occurs, the device can no longer maintain an equilibrium position and will move to its fully actuated position, limiting the full scanning range available. Another phenomenon associated with this instability is that once the mirror has pulled-in, the voltage required to maintain that position is lower than the pull-in voltage. The mirror will not return from this position until the actuating voltage has been reduced below the holding-voltage. The result of this holding effect is hysterisis [11,18].

For the electrostatic comb drive mirror presented here, there is a ground plane and a series of vertically offset comb fingers, all contained underneath a flat mirror surface. A voltage potential is applied across the fixed fingers and the moving fingers of the device creating an electrostatic force. This force causes the mirror to rotate about an axis supported by the hidden spring suspension, shown separately in Figure 2(a).

The equation of motion is

$$m\ddot{\theta} + b\dot{\theta} + k_m\theta = T_e(\theta, V) \tag{1}$$

where m is the mass of the plate, b is the damping term due to squeeze-film effect, k is the linear spring constant, and $T_e(\theta,V)$ is the electrostatic torque that is a function of both position and voltage.

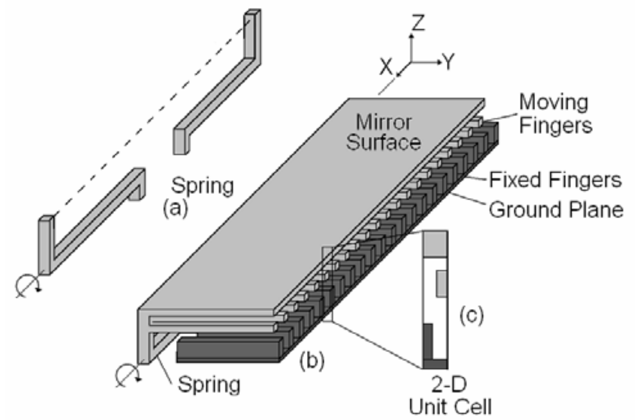

Figure 2. Schematic of 1DOF micro mirror device with hidden vertical comb fingers (not to scale).

The determination of squeeze-film damping coefficient is dependent upon the geometry of the surfaces between which the fluid is trapped. Because of the vertical comb fingers under the surface of the mirror, determining this coefficient analytically is difficult. For the purpose of this discussion, consider the squeeze-film damping term for a torsional plate developed by Pan, et al [19].

$$b = K_{rot}\frac{\mu L w^5}{g^3} \tag{2}$$

where

$$K_{rot} = \frac{48}{\pi^6\left[\left(\frac{w}{L}\right)^2 + 4\right]} \tag{3}$$

L is the length of the plate, w the width, g is the gap between the plates, and μ is the viscosity of the fluid. A more thorough treatment of damping characteristics is needed and will be considered in future work.

The electrostatic torque T_e is given as

$$T_e(\theta, V) = \frac{1}{2} N \frac{\partial C}{\partial \theta} V^2 \quad (4)$$

where V is the applied voltage, and C is the capacitance which can be determined from simulation to be a function of the rotation angle [11,18]. Because of the symmetry of the comb fingers, a unit cell is defined as shown in Figure 2, and N is the total number of unit cells. The results of the capacitance for one unit cell are plotted in Figure 3 along with a fourth order polynomial approximation of the data. The capacitance function is

$$C(\theta) = P_1\theta^4 + P_2\theta^3 + P_3\theta^2 + P_4\theta + P_5 \quad (5)$$

where the coefficients of the polynomial are P = [0.0442 -0.0322 0.0071 0.0004 0.0006] in pF. Table 1 lists the values of additional parameters for this system.

When the electrostatic torque is equal to the mechanical restoring torque, the system is in equilibrium. Once the electrostatic torque becomes greater than the mechanical restoring torque, electrostatic 'pull-in' occurs.

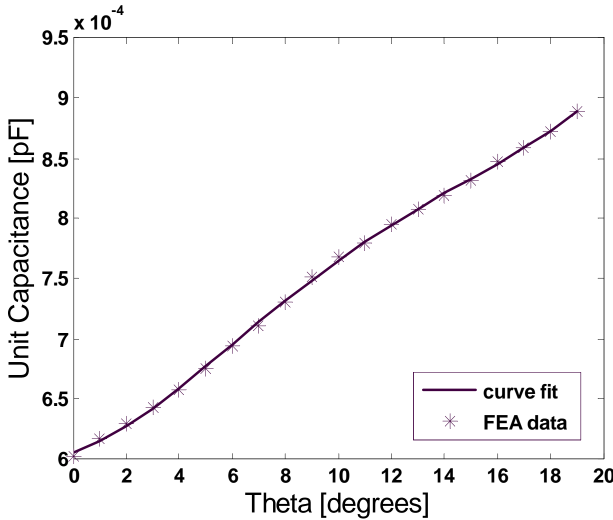

Figure 3. Capacitance calculation as a function of rotation angle, θ, calculated using 3D FEA and a fourth order polynomial curve fit.

3. CONTROL STRATEGIES

Because of the nonlinear nature of the actuator dynamics, nonlinear control methods may be employed that require finding a Lyapunov function and performing stability analysis [20]. Proving global asymptotic stability can be a difficult task, and implementation of the resulting controller can also prove challenging using analog circuits [21]. An alternative to nonlinear control is to use more easily developed linear control design [22].

Table 1. List of parameters used for analysis

Parameter	Value
ρ, density of polysilicon	2331 kg/m^3
k_m, mechanical spring constant	75.79 pN-μm/rad
μ, viscosity of air	1.73e-5 N-s/m^2
L, length of mirror	20 μm
w, width of mirror	100 μm
g, gap between plates	11.25 μm
N, number of unit cells	27

In order to apply linear control technique, the actuator model must first be linearized. The resulting controller design based on a linear plant model must be designed to be sufficiently robust with respect to the uncertainties introduced by the linearization.

Figure 4 shows a block diagrams of how the feedback control can be implemented. When a nonlinear plant is linearized and then the controller is applied to the actual system dynamics, robustness and stability become large issues. In order to use linear time-invariant (LTI) control design, the plant can be linearized using the Taylor Series Expansion about an operating point (θ_0, V_0) [23]. Doing so yields the following linear system model,

$$\begin{aligned} m\ddot{\theta} + b\dot{\theta} + k_m\theta &= T_e(\theta_0, V_0) \\ &+ \left(\left. \frac{\partial T_e}{\partial \theta} \right|_{\theta=\theta_0, V=V_0} \right)(\theta - \theta_0) \\ &+ \left(\left. \frac{\partial T_e}{\partial V} \right|_{\theta=\theta_0, V=V_0} \right)(V - V_0) \end{aligned} \quad (6)$$

The evaluation of the partial derivative terms in (6) will produce a term that is dependent only on the rotation angle that can be considered the electrostatic spring force, k_e [22].

$$k_e = \tfrac{1}{2} N \left(\left. \frac{\partial^2 C}{\partial \theta^2} \right|_{\theta=\theta_0, V=V_0} \right) V_0^2 \quad (7)$$

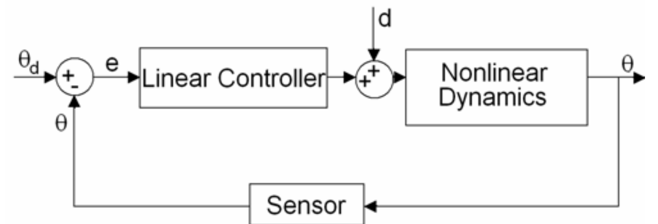

Figure 4. Block diagram representation of system.

Equations (6) can be written as the linearized system

$$m\ddot{\theta} + b\dot{\theta} + (k_m - k_e)\theta = C_1 + C_2 V \tag{8}$$

where C_1 and C_2 are constant terms dependent upon the operating point and may be expressed in terms of the polynomial curve-fit from equation (5).

$$C_1 = -\tfrac{1}{2} N V_0^2 \left(16 P_1 \theta_0^3 + 9 P_2 \theta_0^2 + 4 P_3 \theta_0 + P_4\right) \tag{9}$$

$$C_2 = N \left(\left. \frac{\partial C}{\partial \theta} \right|_{\theta=\theta_0, V=V_0} \right) V_0 . \tag{10}$$

When linearizing a function about an operating point, it is desirable that the linear model will provide an adequate estimate of the nonlinear function within a small range about that operating point. For systems that are operating over a large range or that have very nonlinear characteristics, this linearization may not provide an adequate estimate of the nonlinear function. Figure 5 shows an illustration of the nonlinear electrostatic torque for an electrostatic comb drive and its linearized estimate about a single operating point θ_0. This linear estimate of the nonlinear system does not capture the torque characteristics very well over the range of operation. An alternative method is to segment the operating range and do a piece-wise linearization about multiple operating points to gain a better estimate for the nonlinear function, as illustrated in Figure 6. This piece-wise linear model can be used to perform gain scheduling in which the controller gains will switch depending on the region of operation [28].

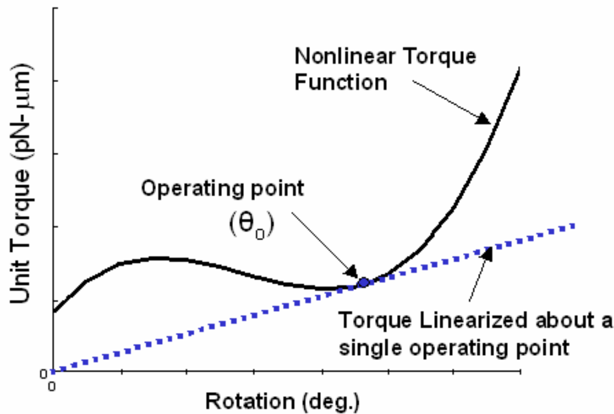

Figure 5. Illustration of torque as a function of rotation angle for nonlinear model and model linearized about a single operating point.

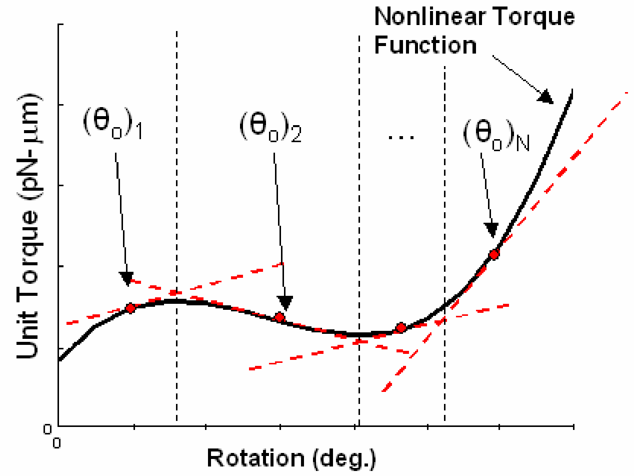

Figure 6. Illustration of torque as a function of rotation for nonlinear model and a piece-wise model linearized about multiple operating points.

4. SENSOR DEVELOPMENT

In addition to considering controller development, it is important to also consider the type of sensing to be used in the feedback loop. One possible technique is through the use of laser beam steering and optical detection using a photosensitive diode (PSD) [17,27]. For stationary applications in which overall system size is not a limitation, these techniques can be implemented on an optical workbench setup. However, one of the advantages of MEMS technology is that it holds the promise of developing small, portable systems. Accomplishing this requires developing systems with built-in or on-chip sensing, and needs more complex system-level and packaging integration consideration. Other sensing techniques that can also be implemented on-chip include capacitive and piezoresistive sensing.

Capacitive sensing can provide high-resolution feedback but often requires complex circuitry to process the signal. Alternatively, piezoresistive sensing methods have been proven a viable option for surface micromachined polysilicon. Stalford *et al.* [24] demonstrated the use of piezoresistive sensing created entirely within a modified SUMMiT fabrication process [13]. Drawbacks to piezoresistive sensing include a relatively large area needed for the resistor elements and piezoresistive sensing can be time dependent. Piezoresistive materials have an electrical resistance that varies when placed under mechanical strain. This relationship can be treated as linear for small strains. The ratio, δ_R, of the change in resistance, ΔR, to the nominal resistance, R, is given as

$$\delta_R = \frac{\Delta R}{R} = G\varepsilon \tag{11}$$

where G is the gauge factor of the material and ε is the strain [25]. Previous study shows polysilicon to have an approximate gauge factor of 25 [26]. An advantage of using piezoresistive sensing is that the signal detection can be accomplished using a Wheatstone

bridge circuit. A single-active Wheatstone bridge is shown in Figure 7.

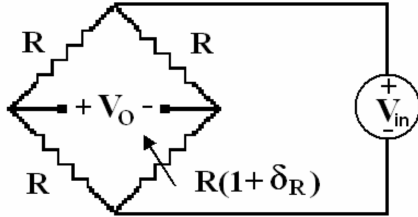

Figure 7. Single active Wheatstone bridge diagram.

Assuming all resistors have the same nominal resistance value, R, the relationship between the applied voltage, V_{in}, and the output voltage, V_o, is given as

$$\frac{V_o}{V_{in}} = \left(\frac{1}{2} - \frac{R(1+\delta_R)}{R + R(1+\delta_R)} \right) \tag{12}$$

With the assumption that δ_R is a very small number, this further reduces to

$$\frac{V_o}{V_{in}} \approx \frac{\delta_R}{4} . \tag{13}$$

5. CONCLUSIONS AND FUTURE WORK

This paper explores the fundamental issues in the development of feedback control for applications in MEMS optical systems. The electrostatic micro mirror device model contains nonlinear terms that create an added challenge to the implementation of control strategies. As work-in-progress, the proposed method for a controller design is to generate a piece-wise linearized model about multiple operating points. This model then can be used to design linear controllers for each segment of the operating range and implemented using gain scheduling.

Future work includes improved development of the dynamic model by investigating more complex estimates of the squeeze-film damping effect on the actuator dynamics. Controller development will be carried out using the linearized system and applying the controller to the nonlinear plant. Once a suitable controller is developed, it can then be implemented experimentally on a physical system using optical feedback techniques and piezoresistive on-chip sensing.

6. ACKNOWLEDGEMENTS

This work is supported by the Sandia National Laboratories Vice Presidential Campus Executive Fellowship and the United States Department of Energy under Contract DE-AC04-94AL85000. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.

7. REFERENCES

[1] D. Hah, S.T. Huang, J-C. Tsai, H. Toshiyoshi, and M.C. Wu, “Low-Voltage, Large-Scan Angle MEMS Analog Micromirror Arrays with Hidden Vertical Comb-Drive Actuators”, *Journal of Microelectromechanical Systems*, Vol. 3, No. 2, April 2004, pp. 279-289.

[2] D. Hah, P.R. Patterson, H.D. Nguyen, H. Toshiyoshi, and M.C. Wu, “Theory and Experiments of Angular Vertical Comb-Drive Actuators for Scanning Micromirrors”, *IEEE Journal of Selected Topics in Quantum Electronics*, Vol. 10, No. 3, May/June 2004, pp. 505-513.

[3] J. Kim, and L. Lin, “A MEMS Tunable Capacitor Based on Plastically Deformed Vertical Comb Sets”, *Proceedings of 2004 ASME International Mechanical Engineering Congress and Exposition*, Nov. 13-20, Anaheim, CA.

[4] W.C. Tang, M.G. Lim, and R.T. Howe, “Electrostatic Comb Drive Levitation and Control Method”, *Journal of Microelectromechanical Systems*, Vol. 1, No. 4, Dec. 1992, pp. 170-178.

[5] D. Hah, H. Toshiyoshi, and M.C. Wu, “Design of Electrostatic Actuators for MOEMS Applications”, *Design, Test, Integration and Packaging of MEMS/MOEMS 2002, Proceedings of SPIE*, Vol. 4755, pp. 200-207.

[6] Sandia National Laboratories, http://www.sandia.gov/media/NewsRel/NR1999/space.html, April 5, 2006.

[7] Sandia National Laboratories, http://www.sandia.gov/mstc/technologies/microsensors/chem._list.html, March 16, 2006.

[8] N.D. Dagalakis, T. LeBrun, and J. Lippiatt, *Micro-Mirror Array Control of Optical Tweezer Trapping Beams*, Second IEEE Conference on Nanotechnology, Washington DC, August 26-28, 2002, pp.177-180.

[9] D. Dudley, W. Duncan, and J. Slaughter, *Emerging Digital Micromirror Device (DMD) Applications*, Proceedings of the SPIE, Vol. 4985, 2003.

[10] J. Bronson, G. Wiens, J. Allen, *Modeling and Alleviating Instability in a MEMS Vertical Comb Drive using a Progressive Linkage,* Proceedings of IDETC/CIE 2005 ASME 2005 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference September 24-28, 2005, Long Beach, California, USA.

[11] J. Bronson, *Effects of Electrostatic Instability on the Performance of MEMS Actuators*, Proc. of 2005 Florida Conf. on Recent Advances in Robotics, May 5-6, 2005, University of Florida, Gainesville, FL.

[12] J.M. Bustillo, R.T. Howe, R.S. Muller, “Surface Micromachining for Microelectromechanical Systems”, Proc. of the IEEE, Vol. 86, No. 8, August 1998, pp1554-1574.

[13] Sandia National Laboratories, http://www.sandia.gov/mstc/technologies/micromachines/techinfo/technologies/ summit5.html, February 10, 2005.

[14] E. S. Hung, and S. D. Senturia, “Extending the Travel Range of Analog-Tuned Electrostatic Actuators,” *Journal of*

Microelectromechanical Systems, Vol. 8, No. 4, December 1999, pp. 497-505.

[15] D.M. Burns, and V.M. Bright, “Nonlinear Flexures for Stable Deflection of an Electrostatically Actuated Micromirror”, *Proceedings of the SPIE*, Vol. 3226, 1997 pp. 125-136.

[16] J.I. Seeger, and B.E. Boser, “Dynamics and Control of Parallel-plate Actuators Beyond the Electrostatic Instability”, *Transducers ’99, The 10th International Conf. on Solid-State Sensors and Actuators*, Sendai, Japan, June 7-9, 1999, pp. 474-477.

[17] J.W. Wittwer, T. Gomm, and L.L. Howell, “Surface Micromachined Force Gauges: Uncertainty and Reliability”, J. of Micromechanics and Microengineering, Vol. 12, pp.13-20, 2002.

[18] N. Arancibia, S. Gibson, and T.C. Tsao, “Adaptive Control of MEMS Mirrors for Beam Steering”, *Proceedings of 2004 ASME IMECE*, Nov. 13-20, Anaheim, CA.

[19] F. Pan, J. Kubby, E. Peeters, A.T. Tran, and S. Mukherjee, “Squeeze-film Damping Effect on the Dynamic Response of a MEMS Torsion Mirror”, *Tech. Proc. International Conf. on Modeling and Simulation of Microsystems*, 1998, pp. 474-479.

[20] A.M. Lyapunov, “The general problem of motion stability”, *Ann. Math. Study*, Princeton, NJ, Princeton University, 1949.

[21] I. Fantoni, R. Lorano, and M.W. Spong, “Energy Based control of the pendubot”, *IEEE Trans. Automat. Control,* vol. 45, pp. 725-729, Apr. 2000.

[22] M. Lu and G. Fedder, “Position Control of Parallel-Plate Microactuators for Probe-Based Data Storage”, *J. MEMS,*Vol. 13, No. 5, Oct. 2004, pp. 759-769.

[23] K. Ogata, *Modern Control Engineering, Fourth Ed.*, Prentice Hall, Upper Saddle River, New Jersey, 2002.

[24] H.L. Stalford, C. Apblett, S.S. Mani, W.K. Schubert, and M. Jenkins, “Sensitivity of Piezoresistive Readout Device for Microfabricated Acoustic Spectrum Analyzer,” Proc. of SPIE, vol. 5344, pp.36-43.

[25] S.D. Senturia, *Microsystem Design,* Kluwer Academic Publishers, Boston, MA, 2001.

[26] G. Roman, J. Bronson, G. Wiens, J. Jones, J. Allen, *Design of a Piezoresistive Surface Micromachined Three-Axis Force Transducer for Microassembly*, Proceedings of IMECE 2005: International Mechanical Engineering Conference and Exposition November 5-11, 2005, Orlando, Florida.

[27] A. Tuantranont, V.M. Bright, J. Zhang, W. Zhang, J. Neff, and Y.C. Lee, “MEMS-Controllable Microlens Array for Beam Steering and Precision Alignment in Optical Interconnect Systems”, *Proceedings of the 2000 Solid-State Sensor and Actuator Workshop*, Hilton Head Island, SC, pp. 101-104, June 4-8, 2000.

[28] W.J. Rugh, “Analytical framework for gain scheduling”, *Control Systems Magazine, IEEE*, Vol. 11, No. 1, Jan 1991, pp. 79-84.