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Optimal Design of Smart Tools for Minimally Invasive Surgery

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1. Abstract

A new integrated grasping tool for minimally invasive surgery has been designed consisting of two piezoelectric bimorph actuators. To improve the force and deflection performance of the bimorphs, a segmented design with varying piezoelectric layer thicknesses is proposed, and an optimization procedure developed for sizing the section thicknesses. Design of experiments and response surface methodologies were used in order to model the design space and the sequential quadratic programming method was used to perform the optimization. Design objectives include maximum tip deflection, maximum gripping force, and maximum work available at the tip. By allowing the thickness of the piezoelectric layers of the bimorph to vary as well as the voltage applied to each segment, optimum thickness configurations were determined that led to increased bimorph gripper performance.

2. Keywords

Piezoelectric Bimorph, Minimally Invasive Surgery, Compliant Mechanism

3. Introduction

Current tools employed in minimally invasive surgery (MIS) procedures (e.g. laparoscopic and endoscopic) include various types of end-effectors such as forceps, graspers, scissors, electrocautery devices, staplers, and needle holders. These tools typically consist of small rigid components connected by mechanical hinge joints, which are linked to an actuation handle via long tendon wires or push rods. As an alternative to complex rigid-link end-effectors which are mechanically actuated, new designs are being developed using compliant mechanisms actuated by smart materials. Compliant mechanisms are defined as single-piece flexible devices which use elastic deformation to achieve force and motion transmission. They are well-suited for use as end-effectors in MIS due to the relatively small ranges of motion required in most surgical tasks. More importantly, they offer the considerable advantages of single-piece construction and ease of manufacture over traditional rigid-link devices, eliminating the need for complex millimeter-scale assembly and cleaning in hinge areas. Compliant mechanisms also lend themselves to integration with smart material actuators such as piezoelectric ceramics. Smart materials can be used as both sensors and actuators, and have the benefits of high power density and fast response time over conventional actuators. By using a compliant end-effector equipped with smart material actuation, a surgical tool can be locally actuated and precisely controlled. Moreover, force sensing is readily accomplished by utilizing the sensing capability of smart materials, and the force signal can be relayed back to the surgeon via a tele-robotic interface.

A compliant suture needle holder coupled with a millimeter-scale piezoelectric inchworm actuator has been designed [1]. This design consists of a compliant mechanism actuated by a separate actuator, but fabrication and assembly of this separate inchworm actuator has proven to be difficult on the millimeter-scale. New designs are needed to overcome this and other difficulties. Several researchers have previously developed innovative designs for MIS tools to address the need for improved dexterity, control, and sensing. To provide both improved dexterity and tactile sensing for MIS procedures, robotic hand-like end-effectors have been developed by Cohn et al. [2] and Sastry et al. [3]. Although these devices have displayed acceptable dexterity, they consist of numerous millimeter-scale components, requiring complex fabrication and assembly. Recently, Balazs et al. [4] have developed an elastic jaw grasping forceps which utilize two elastic beams in place of a mechanical hinge joint. This device is actuated by a push rod and is designed to provide a uniform grasping force over the surface of the jaws.

Rather than utilizing a separate end-effector and actuator consisting of numerous millimeter-scale components, the current paper focuses on an integrated surgical gripper design, where the end-effector and actuator material are integrated together to simplify fabrication and assembly. This work is directed at design of surgical gripping devices, since most surgical tasks consist of gripping or cutting-type procedures. A set of quantitative design requirements has been defined for this application, and is summarized in Table 1. A gripping tool such as a suture needle holder must be small and lightweight, and be able to close completely from a 3 mm opening at the jaws while exerting a suitable force at the tip.

Geometry	3mm opening at jaws, close completely, & jaws parallel when closed on 0.5mm needle
Maximum Size	minimize length, 9.5 mm width, 3.5 mm thickness
Closure Force	0.5N at 0.5mm jaw opening
Speed	≤200 ms gripper opening/closing time

Table 1. Design Requirements for Surgical Gripper

Based on these design requirements, a gripping end-effector consisting of a pair of cantilevered piezoelectric bimorph actuators with sandwich beams has been designed (Figure 1). A piezoelectric bimorph is a structure created by laminating layers of piezoelectric material onto either side of a beam. When opposing voltages are applied to the two layers, a bending moment is induced in the beam (Figure 2). When this laminate beam is mounted in a cantilever fashion the bending moment causes a deflection at the free end of the beam. By using a bimorph gripper approach, the end-effector and actuator material are completely integrated into a monolithic design. Chonan et al. [6] and Seki [7] have utilized this type of design for use in MEMS and robotics. For MIS applications the critical design parameters are the dimensions of the bimorph beam as well as its performance, defined here as the tip force and deflection. These parameters must be optimized to satisfy the design requirements, i.e., the tip of each bimorph beam must deflect a specified amount while generating a suitable force at the tip.

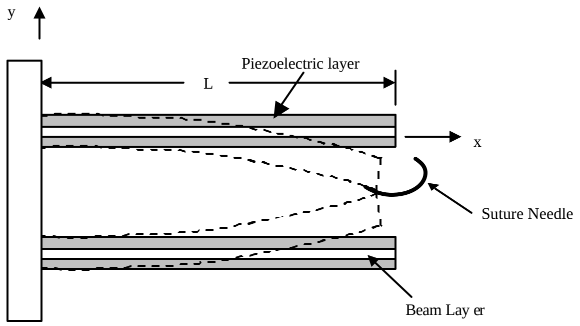

Figure 1. Bimorph Gripper

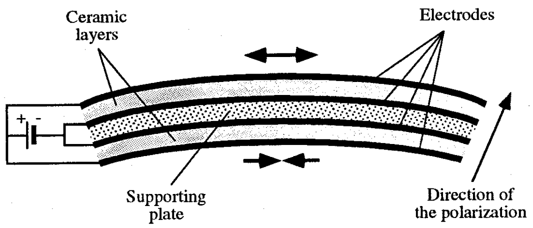

Figure 2. PZT Bimorph [5]

Much of the previous work in the design and analysis of bimorph actuators is for vibration control and for use as transducers [8], [9], [10], [11], [12]. Related work on modeling, design, and optimization of piezoelectric bimorphs and structures use constant thickness piezoelectric layers or elements. Crawley and de Luis [13], Cunningham et al. [14], Correia et al. [15], and Low and Guo [16] model bimorph beams with constant PZT and substrate layer thicknesses. Crawley and de Luis and Crawley and Anderson [17] have developed analysis models of beams with individual piezoelectric elements bonded to the surface of the substrate and with them embedded in a laminate composite beam. In both instances the thickness of the piezoelectric layers remained constant within or on the beam. Topology optimization methods have also been devised to optimize various properties of piezoelectric composite structures [18].

The performance of a PZT bimorph actuator is determined by the thickness and width of the layers, the material properties, and the applied voltage. A simple model of a straight bimorph actuator was used to determine its feasibility for the surgical gripper application. Equations 1 [19] and 2 [20] describe bimorph deflection and blocked force, respectively, for a PZT4 bimorph with 100V input voltage (V), 5.8 cm length (L), 4.5 mm total thickness (t), and a 5 mm width (W). The force available at the tip was modeled as the blocked force (force exerted with no deflection), and the deflection is modeled as the free deflection. Both of these terms represent maximum values. This preliminary analysis demonstrated that a straight bimorph was unable to provide the required gripping force and deflection, i.e., a bimorph that would provide the necessary amounts of deflection and force would be far too large for the surgical application.

$$d = \frac{4L^2 V d_{31}}{t^2} = 0.008mm \tag{1}$$

$$F = \frac{3}{4} d_{31} V \left(\frac{tW}{L}\right) Y_{11} = 0.286N \tag{2}$$

In these equations, the d_{31} and Y_{11} are material properties specific to the PZT4 layers. These equations do no take into account the middle beam layer and assume perfect bonding between the piezoceramic layers.

4. Design Approach and Model Formulation

To improve the deflection and force performance of the bimorph actuator, a variable thickness design is proposed, where the thickness of the piezoelectric layers is varied to optimize the performance. For the MIS gripper application, we would like to maximize the tip deflection for a given length, while simultaneously maximizing the force available at the tip. Maximization of the tip deflection allows for use of the shortest possible actuator which can close the 3mm gap at the tip. And maximization of the tip force allows for secure grasping of a suture needle, while preventing it from rolling in the jaws. However, since both deflection and force are to be simultaneously maximized a multi-criteria type problem formulation is required.

The bimorph model consists of a composite beam with a steel sandwich layer and piezoceramic top and bottom layers divided into 5 distinct sections each with a particular thickness. The thicknesses of each section are the design variables. Various objective functions, including maximum deflection and force, have been investigated in order to extract the peak performance from the bimorph while it is subjected to a specified input voltage. The beam is modeled with standard cantilevered supports inside the finite element analysis. A representative figure of the model is shown in Figure 3. In the finite element model there are 27 total elements. There are 10 piezoelectric elements, 8 non-design piezoelectric transition elements between the segments, and 9 steel beam elements (5 of which are transition). The transition elements are necessary to ensure node compatibility. All of the elements are 8 noded brick elements.

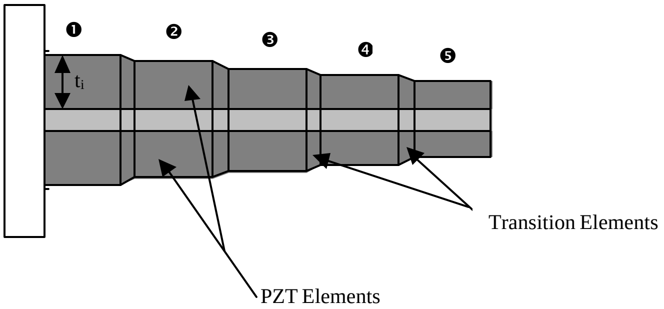

Figure 3. Variable Thickness Bimorph Beam

5. Solution Technique

A design of experiments (DOE) approach was used for optimization due to the small number of design variables and large number of function analysis required. Establishing a set of DOE evaluations started the solution process. The DOE evaluations were based on 5 design variables with three varying thickness levels. The specific DOE that was used for the three levels and five factors problem is a Face-Centered Central Composite [21] [22] design consisting of a total of 27 different runs. This composite design was chosen because it allows for a full second order model of the design space with a minimal number of design points. The evaluations were performed using ABAQUS [23] finite element software. A Matlab [24] program was written to automatically generate the necessary input files to run the DOE in ABAQUS. Two types of ABAQUS FEA runs were developed, one that predicts the free deflection of the bimorph and one that predicts the blocked force. The output data from ABAQUS were compiled and then used to construct a response surface model of the system in S-Plus 4.5 software [25].

The design space was modeled by performing a linear regression analysis of the DOE data in the S-Plus 4.5 software. The models developed are second order quadratic models that include all 2 factor interaction terms. The general form of it is shown below in Equation 3 [21] [26].

$$f = b_0 + \sum_{i=1}^{5} b_i t_i + \sum_{i=1}^{5} b_{ii}^{2} t_i^{2} + \sum_{i=1}^{5} \sum_{j=1}^{5} b_{ij} t_i t_j \qquad (3)$$

where the *t* terms are piezo layer thickness values and the *b* terms are the coefficients obtained from the S-Plus 4.5 software.

This equation was then used for optimization in Matlab. The program used a sequential quadratic programming (SQP) routine to determine the optimum piezo layer thickness values for maximum deflection or force. The system constraints are the upper and lower bounds of the piezo thickness parameters. In order to reasonably assure that a global maximum was obtained, the SQP routine was run at numerous different feasible starting points.

6. Model Validation

The results of the FEA model constructed in ABAQUS were initially verified with a known analytical model for a bimorph deflection with uniform thickness [8]. The comparison yielded a percent error of only 1.42%.

The accuracy of the response surface models was determined to be satisfactory. For all linear regression fits made, the lowest R-squared value was 0.9902, which means that at least 99% of the data was captured for each fit. Another set of random test points was generated using a Latin Hypercube [27] to verify the response surface and evaluated in

ABAQUS and in the response surface models to predict deflection and blocked force. The errors for the RSM can be seen below in Table 2.

	Deflection	Blocked Force
Maximum % Error	20.32	17.41
Average % Error	11.80	2.80
RMSE	5.47E-04	4.27E-02

Table 2. Response Surface Model Errors

The maximum percent error values are a bit high while the average percent errors for each are much lower. This can be attributed to flaws in the linear regression fit to the data. Ongoing work includes exploring more accurate models of the design space.

7. Results

As stated previously, for each set of DOE parameters (thickness values) two distinct FEA models were evaluated. The first determined free displacement while the second determined blocked force. In the model to determine the free deflection, standard cantilevered supports were used. In order to evaluate the blocked force of the bimorph, a pin joint support was added to the free end of the cantilever and the reaction force recorded. The system parameters for the DOE can be seen in Table 3.

Piezoelectric layer material: PZT4	Middle Beam Material: Steel
Middle Beam Thickness=0.5mm	Input Voltage=100V
High Piezo Thickness=3mm	Element Length=10mm
Medium Piezo Thickness=2mm	Transition Element Length=2mm
Low Piezo Thickness=1mm	Width=5mm

Table 3. DOE Parameters for 58 mm Long Segmented Bimorph

7.1 Constant Voltage

The maximum deflection and blocked force thickness parameters were determined independently and can be seen below in Table 4, where the section thickness values are in mm. Figures 4 and 5 illustrate the optimum configurations for each case. All optimum section thickness values went to either the high (3 mm) or low (1 mm) bounds of the design space. For maximizing the free deflection of a segmented bimorph beam, uniformly thin section layers are the optimum. When maximizing the blocked force produced from the beam, the optimum parameter settings are three thick layers closest to the root of the beam and two thin layers at the free end.

	Function Value	t1	t2	t3	t4	t5
Maximum Deflection (mm)	0.0088	1	1	1	1	1
Maximum Blocked Force (N)	2.2587	3	3	3	1	1

Table 4. Maximum Deflection and Maximum Blocked Force Results

Figure 4. Maximum Deflection

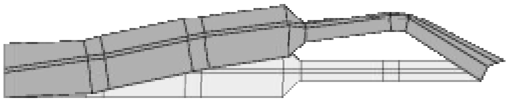

Figure 5. Maximum Blocked Force

Since one cannot achieve both maximum force and deflection at the same settings a tradeoff solution must be found. Therefore, two new approaches to maximize the performance of the bimorph were explored. The first approach is to simply maximize the work produced by the beam, measured in N*mm. The work was modeled as the product of the free displacement and blocked force. Since maximum blocked force and maximum free deflection are not simultaneously achievable, the work term is a theoretical maximum. The actual work available is necessarily less than the product of the free deflection and the blocked force. Another way to formulate a compromise objective was also used. The second approach to maximize a normalized weighted sum of the deflection and blocked force was explored. Equation 4 describes this quantity.

$$f = \left(w \frac{d_{free}}{d_{free_{med}}} + (1-w)\frac{F_{Blocked}}{F_{Blocked_{med}}}\right) \tag{4}$$

Here, the w is a scalar weighting coefficient and the individual objectives are divided by their medium settings to normalize them. In this evaluation, the deflection and force were weighted evenly, i.e.: $w = 0.5$. After creating a response surface model for the data from these two new cases, new optimum solutions were obtained. The settings were recorded in Table 5. In order to maximize the "work" produced by the segmented bimorph beam, a compromise between the maximum deflection and maximum blocked force solutions is obtained. When weighting the deflection and force evenly, the lower bound solution is obtained again indicating that the free deflection response dominates. As the weighting is increased on the deflection, the maximum deflection answer will be approached. The similar response occurs when the weighting on the force is increased. Figure 6 shows the optimum configuration that produces the maximum work from the bimorph.

	Function Value	t1	t2	t3	t4	t5
Maximum Work (N*mm)	0.0091	2.125	1	1	1	1
Maximum Weighted Sum	1.4621	1	1	1	1	1

Table 5. Maximum Work and Maximum Weighted Sum Results

Figure 6. Maximum Work

To evaluate the gains in performance achieved by optimizing, the variable thickness configuration was compared to a straight bimorph of equivalent volume. The blocked forces produced from two different bimorphs with the same volume (1425 mm^3) were compared. The only differences between the two were that one bimorph had the optimum set of thickness parameters previously determined while the other utilized the traditional constant piezo layer thicknesses. These results, seen in Table 6, show that going to the optimum configuration produces a 62% gain in the blocked force created from the bimorph.

		Function Value	t1	t2	t3	t4	t5
Optimized Design	**Maximum Force (N)**	2.2587	3.000	3.000	3.000	1.000	1.000
Constant Thickness Design	**Maximum Force (N)**	1.398	2.207	2.207	2.207	2.207	2.207

Table 6. Constant Volume Blocked Force Comparison

7.2 Saturation Voltage

Further gains in performance can be obtained by varying the voltage across the PZT layers in addition to varying the thicknesses. This phenomenon can be explained by considering the behavior of piezoelectric materials. The free strain produced is represented by Equation 5:

$$\Lambda = \frac{d_{31}V}{t_c} \tag{5}$$

where Λ is the free strain, d_{31} is a PZT coefficient, V is the applied voltage, and t_c is the thickness of the PZT layer. As the DOE's indicated, a reduction in the piezo layer thickness increases the free strain, resulting in an increased displacement at the end of the cantilever beam. The limit of this process is reached when the piezoelectric material reaches its saturation. At this point, the electric field, E_{sat}, is represented by equation 6.

$$E_{sat} = \frac{V_{sat}}{t_c} \tag{6}$$

This equation illustrates the relationship between the thickness of the piezoelectric layers and the maximum voltage that can be applied. Because there is a maximum operating electric field, E_{sat}, associated with a given piezoelectric material and layer thickness, the maximum voltage, the saturation voltage, V_{sat}, which can be applied is limited by the thickness. However, further reducing the thickness of the piezoelectric layer further increases the value of the tip deflection. The applied voltage has a more significant effect on the deflection than does the piezoelectric layer thickness in this range, so the value of the input voltage governs the design in this case.

Therefore, the DOE was run again but this time each of the piezoelectric layers was operating at its particular saturation voltage. These results compared to the previous results can be seen in Table 7.

		Function Value	t1	t2	t3	t4	t5	% Function Value Change
Constant V	**Maximum Deflection (mm)**	0.0088	1	1	1	1	1	250
Sat. V	**Maximum Deflection (mm)**	0.0308	1	1	1	1	1	
Constant V	**Maximum Force (N)**	2.2587	3	3	3	1	1	811
Sat. V	**Maximum Force (N)**	20.58	3	3	3	3	1	
Constant V	**Maximum Work (N*mm)**	0.0091	2	1	1	1	1	5816
Sat. V	**Maximum Work (N*mm)**	0.5384	3	3	3	3	1	
Constant V	**Maximum Weighted Sum**	1.4621	1	1	1	1	1	4.2
Sat. V	**Maximum Weighted Sum**	1.5233	3	3	3	1	1	

Table 7. Constant Voltage vs. Saturation Voltage Results

Figure 7. Maximum Deflection

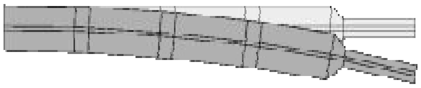

Figure 8. Maximum Blocked Force

Figure 9. Maximum Work

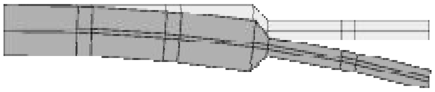

Figure 10. Maximum Weighted Sum

The results when the piezoelectric layers are operating at the saturation voltages show a tremendous increase in the values of the functions that are maximized. The maximum weighted sum and maximum work thickness parameter sets changed the most while the optimum thickness parameter set for deflection remained the same and only t_4 changed in the optimum set for maximizing the force. Figures 7-10 show the new optimum configurations all operating at their saturation voltages.

8. Conclusions and Future Work

The performance of bimorph actuators can be improved by discretizing the bimorph into segments with varied thickness values. The results of this study indicate that thin piezoelectric layers are needed to create maximum free deflection of the bimorph. The magnitude of free deflection is greatly increased if each piezoelectric layer is being operated at it's saturation voltage as opposed to a constant voltage. The same is true for the magnitudes of the blocked force that the bimorph can produce. Here, the optimum parameter settings are three (constant voltage) to four (saturation voltage) thick sections closest to the root of the beam and one (constant voltage) to two (saturation voltage) thin layers at the free end. In order to capture this tradeoff, the "work" that the bimorph produces (deflection X blocked force) was maximized. This yields two different solutions depending on the type of input voltage applied. To more accurately portray the true behavior of the bimorph, a weighted sum of the free deflection and blocked force was computed and maximized. When operating at constant voltage and both objectives evenly weighted, the optimum set of section thicknesses are all at the lower bound. When operating at the piezoelectric material's saturation voltage, the optimum thickness value set consists of three thick sections closest to the root of the bimorph and with two thin sections at the free end.

Ongoing work includes a closer examination of the tradeoff off between free deflection and blocked force through the use of a Pareto frontier study. Fabrication and testing of a segmented bimorph to further validate the ABAQUS FEA and response surface models that were created is also planned. Although significant improvements in performance were obtained by optimizing the thickness of the piezoceramic layers and varying the voltage applied to the layers, additional improvements in tip deflection are required for the MIS gripper application. Future work includes a feasibility study of alternative actuator materials with larger strain capabilities such as piezoelectric polymers.

9. Relation to Optimization in Industry

Significant cost savings to industry can be realized by using optimization in product design. These cost savings are most pronounced when optimization is used early in the design process, when design freedom is high and the cost of changing the design is relatively low. The widespread used of optimization in industry has yet to be realized, however. The conclusions discussed in this paper illustrate one of the challenges that face users of optimization, academic or industrial. That challenge is the formulation of the objective function. In this research two conflicting design objectives are to be maximized. A weighted sum of objective functions was explored as a multi-criteria objective, but the results of the optimization are as of yet inconclusive, indicating that a better objective function may be needed. There are currently many sophisticated methods and algorithms to solve optimization problems, but in order to effectively generate optimized designs, one must know how to express that which they want to optimize. Two approaches are suggested: further study of the formulation of optimization problems with multiple objectives, and more close collaboration between academic researchers and industrial product designers in formulating realistic and meaningful objective functions.

10. Acknowledgements

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11. References

[1] Canfield, S., Edinger, B., Frecker, M., and Koopmann, G. (1999). Design of Piezoelectric Inchworm Actuator and Compliant End Effector for Minimally Invasive Surgery. *Proceedings SPIE 6th International Symposium on Smart Materials and Structures. Newport Beach, California, March, 1999*, Paper 3668-78.

[2] Cohn, M., Crawford, L., Wendlandt, J., and Sastry, S. (1995). Surgical Applications of Milli-Robots. *Journal of Robotic Systems*, 12 (6), 401-416.

[3] Sastry, S., Cohn, M., and Tendick, F. (1997). Millirobotics for Remote Minimally Invasive Surgery. *Robotics and Autonomous Systems*, 21, 305-316.

[4] Balazs, M., Feussner, H., Hirzinger, G., Omote, K., and Ungeheuer, A. (1998). A New Tool for Minor Access Surgery. *IEEE Engineering in Medicine and Biology*, May/June, 45-48.

[5] Fatikow, S., and Rembold, U. (1997). *Microsystem Technology and Microrobotics*, Springer-Verlag Berlin Heidelberg.

[6] Chonan, S., Jiang, Z. W., and Koseki, M. (1996). Soft-handling Gripper Driven by Piezoceramic Bimorph Strips. *Smart Mater. Struct.* 5, 407-414.

[7] Seki, H. (1992). Piezoelectric Bimorph Microgripper Capable of Force Sensing and Compliance Adjustment. *Japan/USA Symposium on Flexible Automation. ASME 1992*, 1, 707-713.

[8] Mason, W. P., and Thurston, R. N. (1960). A Compact Electromechanical Band-Pass Filter for Frequencies Below 30 Kilocycles. *IRE Transactions on Ultrasonics Engineering*, June, 59-70.

[9] Kim, S. J. and J. D. Jones, (1991). Optimal Design of Piezoactuators for Active Noise and Vibration Control. *AIAA Journal* 29 (12) 2047-2053.

[10] Baz, A., and Poh, S. (1988). Performance of an Active Control System with Piezoelectric Actuators. *Journal of Sound and Vibration,* 126 (2), 327-343.

[11] Cunningham, M. J., Jenkins, D. F. L., Clegg, W. W., and Bakush, M. M. (1995). Active Vibration Control and Actuation of a Small Cantilever for Applications in Scanning Probe Instruments. *Sensors and Actuators A* 50, 147-150.

[12] Jenkins, D. F. L., Cunningham, M. J., and Clegg, W. W. (1995). The use of Composite Piezoelectric Thick Films for Actuation and Control of Miniature Cantilevers. *Microelectronic Engineering* 29, 71-74.

[13] Crawley, E. F. and de Luis, J. (1987). Use of Piezoelectric Actuators as Elements of Intelligent Structures. *AIAA Journal* 25 (10), 1373-1385.

[14] Cunningham, M. J., Jenkins, D. F. L., and Bakush, M. M. (1997). Experimental Investigation of Optimal Thickness of a Piezoelectric Element for Cantilever Actuation. *IEEE Proc-Sci. Meas. Technol.* 144 (1), 45-48.

[15] Franco Correia, V., Mota Soares, C. M., and Mota Soares, C. A. (1998). Modeling and Design of Adaptive Composite Structures. *Proceedings NATO Advanced Study Institute on Mechanics of Composite Materials and Structures, Troia, Portugal, Vol. II*, 59-92.

[16] Low, T. S. and Guo, W. (1995). Modeling of a Three-Layer Piezoelectric Bimorph Beam with Hysteresis. *Journal of Microelectromechanical Systems.* 4 (4), 230-237.

[17] Crawley, E. F. and Anderson, E. H. (1990). Detailed Models of Piezoceramic Actuation of Beams. *J. of Intell. Mater. Syst. and Struct.* 1, January, 4-25.

[18] Silva, E., Fonseca, J., Kikuchi, N. (1997). Optimal Design of Piezoelectric Microstructures. *Computational Mechanics*, 19, 397-410.

[19] Piezo Systems, Inc. (1998). Catalog #3, August. 186 Massachusetts Avenue, Cambridge, MA 02139

[20] Piezoelectric Ceramic Sensors. MuRata Elelectronics North America, Inc. 2200 Lake Park Drive, Smyrna, GA 30080-7604.

[21] Simpson, T. W., Peplinski, J., Koch, P. N., and Allen, J. K. (1997). On the Use of Statistics in Design and the Implications for Deterministic Computer Experiments. *Proceedings of the DETC'97, 1997 ASME Design Engineering Technical Conferences, Sacramento, California, September 14-17, 1997.* DETC97/DTM-3881.

[22] Montgomery, D. C., (1997). *Design and Analysis of Experiments.* Fourth Edition, John Wiley & Sons, NY.

[23] ABAQUS Version 5.7-1 (1997). Hibbitt, Karlsson and Sorensen, Inc., 1080 Main Street, Pawtucket, Rhode Island 02860.

[24] Matlab Version 5.1.0 (1997). The Math Works Inc., 24 Prime Park Way, Natick, MA 01760-1500.

[25] S-Plus 4.5 (1997). Data Analysis Products Division, Mathsoft Inc., Seattle, Washington.

[26] Myers, R. H. and Montgomery, D. C. (1995). *Response Surface Methodology: Process and Product Optimization Using Designed Experiments.* John Wiley & Sons, NY.

[27] McKay, M. D., Beckman, R. J. and Conover, W. J. (1979). A Comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output from a Computer Code. *Technometrics*, 21 (2), 239-245.