

**AC 2008-814: MODELING AND CONTROL OF SMART ACTUATORS:  
INTEGRATING NANO/BIO TECHNOLOGY INTO THE ME CURRICULUM**

**Ying Wu, Iowa State University**

**Stephanie Culter, Virginia Commonwealth University**

**Qingze Zou, Iowa State University**

**Gina Pannozzo, Virginia Commonwealth University**

**Kam Leang, Virginia Commonwealth University**

**Santosh Devasia, University of Washington**

# Modeling and Control of Smart Actuators: Integrating Nano/Bio Technology into the ME Curriculum

## Abstract

A recent projection noted that over 7 million jobs will be created in the nano and bio-related field world wide by 2015. The expected growth of such jobs suggests a critical need to prepare and train the workforce for these emerging fields. This paper describes a collaborative approach between three universities to integrate nano/bio technology into the mechanical engineering (ME) undergraduate curriculum by incorporating teaching modules into core ME courses. The teaching modules focus on the fundamental concepts in modeling and control of smart material based actuators (or smart actuators), and they were designed for ME courses in system dynamics, controls, and mechatronics. The piezoelectric actuator, a type of smart actuator, has become increasingly important because of its ability for precision positioning (actuation) or sensing in nano and bio-related technologies. The developed modules use the piezoactuator as an example smart actuator. First, students are taught the fundamental concepts of modeling the input-to-output behavior of piezoactuators. This component begins with a discussion of the piezoelectric effect, followed by the modeling of the vibrational dynamics effects based on the frequency response concept. Students are also introduced to hysteresis, a nonlinear behavior inherent in piezoactuators and other smart actuators. Second, to complement the topics in modeling, lectures were developed to convey the state-of-the-art in high-precision control of piezoactuators for various nanopositioning applications, such as scanning probe microscopes. Four experiments were designed to provide students with hands-on experience with modeling and control of piezoactuators. The teaching materials were implemented at the three universities and preliminary assessment results are presented to demonstrate the initial impact of the project. Particularly, the results of the pre and post tests, surveys, and focus group studies in the context of the expected learning outcomes are presented. In general, the results suggested that student learning and perceptions were positively impacted by the developed teaching materials.

## Introduction

Emerging nano and bio technologies<sup>1</sup> has prompted the need to prepare the future work-force with the knowledge, understanding, and skills necessary for tackling problems in these professional fields. It is projected that by the year 2015 over 7 million jobs will be created in the nano/bio-related field world wide<sup>2</sup>. Such growth of jobs and technologies will have a profound impact on all sectors of the economy (as well as society)<sup>3</sup>. To prepare the future work force with the necessary skill set, this paper focuses on a collaborative approach which involves three universities to develop, integrate, and assess a teaching module on smart actuators for three different courses in the ME undergraduate curriculum: system dynamics and controls, mechatronics, and capstone design. The teaching module is specifically designed to address the important aspects of modeling, control, and design of smart actuator-based systems. In particular, the module consists of lecture and laboratory components, and each component can be easily integrated into a course in part or whole.

Smart actuators such as piezoelectric actuator (piezoactuator), shape memory alloy (SMA) actuator, and magnetostrictive based devices are important because they are widely used in a multitude of emerging nano and bio technologies. For example, piezoactuators are used in atomic force microscopy (AFM) to image and manipulate samples at the nanoscale<sup>4</sup> — AFM is one of the most important instruments in nanotechnology; and SMA actuators are used in micro-pumps<sup>5</sup> and minimum invasive surgical tools in biomedical applications<sup>6</sup>. Thus, smart actuators are critical and their role in micro and nanoscale systems is as important as the electric motor is for common macro-scale devices and systems such as home appliances and automobiles. But contrast to the well-established coverage of electric motors in the ME curriculum, modeling and control of smart actuators has not yet been systematically integrated into core ME courses. For instance, electric motors are covered several ME texts<sup>7,8</sup> and the subject is tightly woven into core ME classes such as system dynamics and mechatronics. But the study of smart actuators in core courses is currently few and far between. To take a lead in integrating the material into core courses, and to expose students to the fundamentals and importance of smart actuators, we exploit a collaboration between three universities to develop, integrate, and assess a teaching module that focuses on the modeling, characterization, and control of smart actuators.

Developing a module was preferred over creating a new core course because modular teaching material can be easily integrated into a core course and it easier to create than a new course. The traditional mechanical engineering curriculum is often full and accommodating a new core course requires approval at the department as well as the school and university level. Therefore, developing a module was a more favorable solution to expose students to new concepts and technologies. It can be argued that a technical elective course can be easily created; however such courses impact a smaller number of students compared to core courses. By integrating a module into an appropriate core course, a larger number of students are impacted and the module can be easily tailored to meet the specific learning objectives of the course.

Mechanical engineering programs throughout the country have integrated nanotechnology related topics into the undergraduate curriculum, for example, the “Nano-to-Macro Transport Processes” course at MIT, the “Nanomanufacturing and MEMS Technology” (ME 528) course at ISU, the “Micro/Nano Science and Engineering” (ME 495) course at Northwestern University, and the “Micro/Nano-Robotics” (ME 24779-A) course at Carnegie Mellon University (CMU). These courses address critical issues in nanotechnology-related fields, such as manufacturing, design, and control. In contrast, the proposed module specifically addresses the fundamentals of smart actuators, a topic that has not been considered.

The remainder of this paper is organized as follows. An overview is presented which briefly describes the collaboration and the expected learning outcomes. Next, the components of the piezoactuator module are presented in detail. Afterwards, the next section describes how the teaching materials were implemented. Preliminary assessment results are also presented in the same section. Finally, project challenges and concluding remarks are included at the end of the article.

## **Overview of the Module**

### *The Collaboration*

The components of the piezoactuator module was developed between Iowa State University (ISU), Virginia Commonwealth University (VCU), and The University of Washington (UW). The benefits of the collaboration include: (1) maximizing the number of students involved in the project, (2) impacting a larger student population, (3) sharing of ideas to improve the quality of the module, and (4) obtaining a larger data set for assessment. First, it was decided that the module should focus on one type of smart actuator, the piezoactuator. The piezoactuator was chosen because the collaborators had extensive experience with modeling and control of piezoactuators in their own research<sup>9</sup>. Future work will focus on developing modules for other smart actuators, such as shape memory alloys and electroactive polymers. The three components of the module were divided and the collaborator at each university was responsible for developing and integrating a component of the module at their location. After the initial development and implementation, the teaching materials were then shared between the collaborators and improved accordingly. This paper describes the results of the first development and implementation phase.

The collaborator at UW led the development of the design component. This component focuses on how design-related issues should be addressed and how best to involve students in design projects with piezoactuators and various smart actuators. The modeling component was developed and implemented at ISU. Finally, the control of piezoactuators component was developed and implemented at VCU. The three collaborators shared information during the development and assessment process. The results from all three schools were compiled and analyzed by the collaborator at VCU and an expert from the Education Department at VCU. The results were then communicated with the other two collaborators to further refine the components for the next development and implementation phase.

### *The Expected Learning Outcomes*

After being exposed to the piezoactuator module, students should be able to: (a) understand the fundamental concepts of modeling and control of piezoactuators, (b) transfer the knowledge to solve engineering problems at higher levels of abstraction, (c) recognize mechanical engineering concepts in nano and bio technologies, and (d) perform experiments. The piezoactuator module consists of three main components: modeling, control, and design. Each component consists of a set of lectures and laboratory experiments, where the latter gives students hands-on experience with piezoactuators, as well as teaches them commonly-used experimental techniques for system identification.

## **The Piezoactuator Module**

### *Characterization and Modeling*

Piezoactuators are devices made from piezoelectric materials that respond by changing their dimensions when voltage is applied. When the materials are stressed, they produce a measurable

voltage. The former behavior is exploited to produce piezoactuators and the latter is used for sensors. Students were taught the piezoelectric effect, a behavior that enables piezoelectric materials to be used as actuators and sensors. In particular, this component teaches the modeling of the input-to-output behavior of piezoactuators. The input is the applied voltage and the output is the displacement of the actuator. The input-to-output behavior of a piezoactuator consists of three effects: creep, hysteresis, and vibrational dynamics.

*Lecture LM1: The Piezoelectric Effect and Constitutive Relationships*

In this lecture, a PowerPoint presentation was present that showed examples to illustrate the importance of piezoelectric materials in nano and bio technology. The examples included scanning probe microscopes, micro-machining, and pressure sensors.

Following the brief PowerPoint presentation, the concept of the piezoelectric effect was presented, where the quartz crystal model was used to describe the effect. This model was first developed by Lord Kelvin in 1893<sup>10,11</sup>, and it is a simple 2D model based on the unique characteristic of certain crystalline lattices that deform under pressure. As a result, the centers of gravity of the positive and negative charges separate, creating a dipole moment (product of charge value and their separation). The resulting dipole moment induces an electric charge that can be measured across the surface of the material. This behavior explains the sensing ability of piezoelectric material. Conversely, an applied voltage induces a mechanical strain in the crystalline lattice<sup>10</sup>. Figure 1 shows the 2D model which was presented in class, where (a) represents the sensing and (b) represents the actuating ability the piezoelectric material. This discussion was also linked to students' background in physics and material engineering (e.g., the concept of charged particles and the crystalline structure of materials such as ceramics<sup>12</sup>).

Next, the linear constitutive relationship which describes the electromechanical properties of the piezoelectric material was presented. We began with Hooke's Law, which was familiar to students, relates strain ( $\delta$ ) to the compliance ( $c$ ) and stress ( $\sigma$ ) for everyday metals and plastics, that is,

$$\delta = c \sigma. \tag{1}$$

Because piezoelectric materials have electrical properties, we also explained the basic constitutive equation for common dielectrics. The equation relates the electric displacement ( $D$ ) to the permittivity ( $\epsilon$ ) and electric field ( $E$ ),

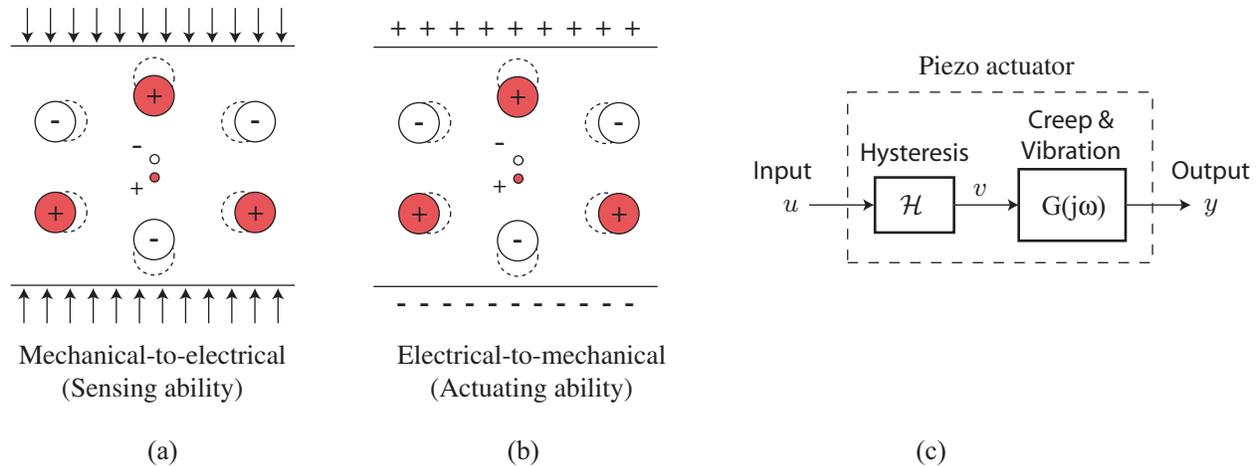
$$D = \epsilon E. \tag{2}$$

Then the two basic constitutive equations (1) and (2) were combined and the following relationship was explained to students

$$\delta = c_E \sigma + d^T E, \tag{3}$$

$$D = d \sigma + \epsilon_\sigma E. \tag{4}$$

We emphasized that Eqs. (3) and (4) are in general matrix equations because of the anisotropic nature of piezoelectric materials, and the subscript  $E$  indicates a zero, or constant, electric field; the subscript  $\sigma$  indicates a zero, or constant, stress field; the superscript  $T$  stands for transposition of a matrix; and  $d$  is piezoelectric modulus, the ratio of strain to applied field or charge density to applied mechanical stress. We also mentioned that in order to describe or model piezoelectric materials, one must have knowledge about the material's mechanical properties (compliance or stiffness), its electrical properties (permittivity), and its piezoelectric coupling properties (piezoelectric modulus). This first lecture was covered in a one-hour period.



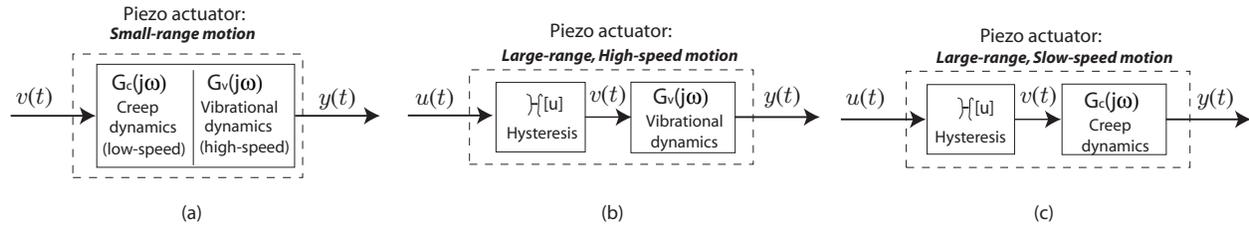
**Figure 1:** A two-dimensional model of a unit cell for a quartz crystal illustrating the piezoelectric effect. The large solid circles in (a) and (b) represent positively charged ions and the small solid circle represents their center of gravity. Likewise, large open circles represent negatively charged ions, and their center of gravity is represented by the small open circle. (a) Mechanical stress induces an electric dipole – separation of centers of gravity for positive and negative ions and (b) applied field produces mechanical strain. (c) Block diagram model of hysteresis, creep, and vibrational dynamics.

*Lecture LM2: Physics-Based Modeling of Creep and Vibrational Dynamics*

When an input voltage is applied to a piezoactuator, the actuator's output displacement exhibits the combined effects of hysteresis, creep, and vibration<sup>13</sup>. These three effects are coupled and the degree by which they appear in the output response depends on the input frequency and output range. This is an importance concept when designing with piezo-based devices. The approach to modeling the three effects was to decoupled them into two main components: a hysteresis element (input nonlinearity) cascaded with a linear dynamics element that captures the creep and vibration effects. The block diagram of the decoupled model presented in class is shown in Fig. 1(c).

Hysteresis is significant when the range of motion of a piezoactuator is large. At high operating speeds, the effect of the vibrational dynamics becomes noticeable. On the other hand, when a piezoactuator operates over long periods of time, then creep is significant. Several combinations

of these behaviors are depicted in Fig. 2. Students were first taught how to model the creep and vibrational dynamics using linear models<sup>13</sup>.



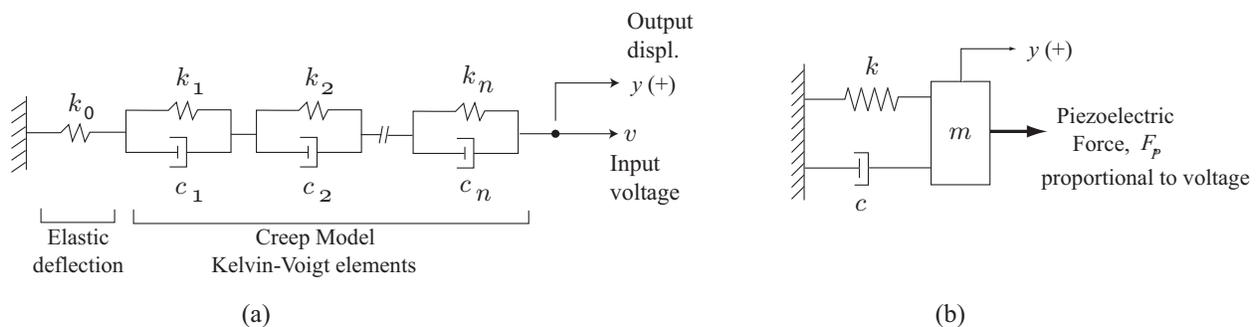
**Figure 2.** The cascade model for creep  $G_c(j\omega)$ , hysteresis  $H[u(j\omega)]$ , and the vibrational dynamics  $G_v(j\omega)$  effects in piezoactuators: (a) the large-range, high-speed motion; (b) the large-range, low-speed motion; and the small-range motion.

It has been shown that the creep and vibrational dynamics effects can be modeled by using mass, spring, and damper elements. This approach to modeling goes hand-in-hand with key concepts in modeling of mechanical systems in the ME undergraduate curriculum. Likewise, this concept aligns with the topic of vibration modes of mechanical systems<sup>14</sup>. The transfer function model for creep in terms of the spring and damper elements is<sup>13,15</sup>

$$G_{creep}(s) = \frac{y(s)}{v(s)} = \frac{1}{k_0} + \sum_{i=1}^N \frac{1}{sc_i + k_i}, \quad (5)$$

where  $k_i$  and  $c_i$  are the spring and damper constants, respectively [see Fig. 3(a)]. Similarly, a simplified model of the vibrational dynamics can be obtained by performing a force balance on the spring-mass-damper system shown in Fig. 3(b). The transfer function model is,

$$G_{vibration}(s) = \frac{y(s)}{v(s)} = A \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} = \frac{\alpha/m}{s^2 + (c/m)s + k/m}. \quad (6)$$



**Figure 3.** Modeling the dynamic behavior of a piezoactuator: (a) creep model and (b) a one-dimensional vibrational dynamics model.

Both models were derived in lecture. Using these models, students were asked to simulate the creep and dynamics behavior in Matlab in a homework assignment. They were asked to investigate the piezo's response to slow time-varying signals (creep behavior) as well as rapid signals like a step, ramp, and triangle input. By doing the homework exercise, they were able to identify the slow drift effect caused by creep and the oscillations in the output due to the dynamics at high frequency.

### *Lecture LM3: Hysteresis Behavior*

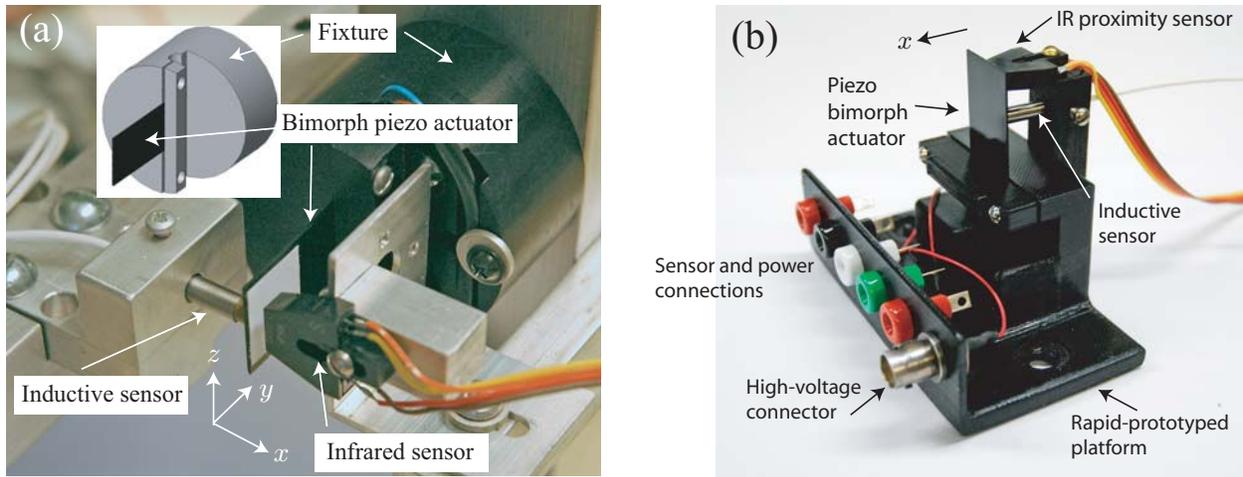
Hysteresis is believed to be attributed to the energy loss caused by micro-scale domain wall interactions [16], and this concept was explained to students. Hysteresis was also compared to plastic deformation in materials<sup>12</sup>. Then the properties of hysteresis such as the local memory property, rate-independence, and range-dependence<sup>17</sup> were discussed. Additionally, students also learned various methods to quantify and characterize the hysteresis behavior and several examples were given in class. Students were informed that hysteresis effect is significant when piezoactuators displace over relatively large range<sup>18,19</sup>, causing large positioning errors in applications such as AFM<sup>20,21</sup>.

### *Experiment EM1: Modeling Linear Vibrational Dynamics using Frequency Response*

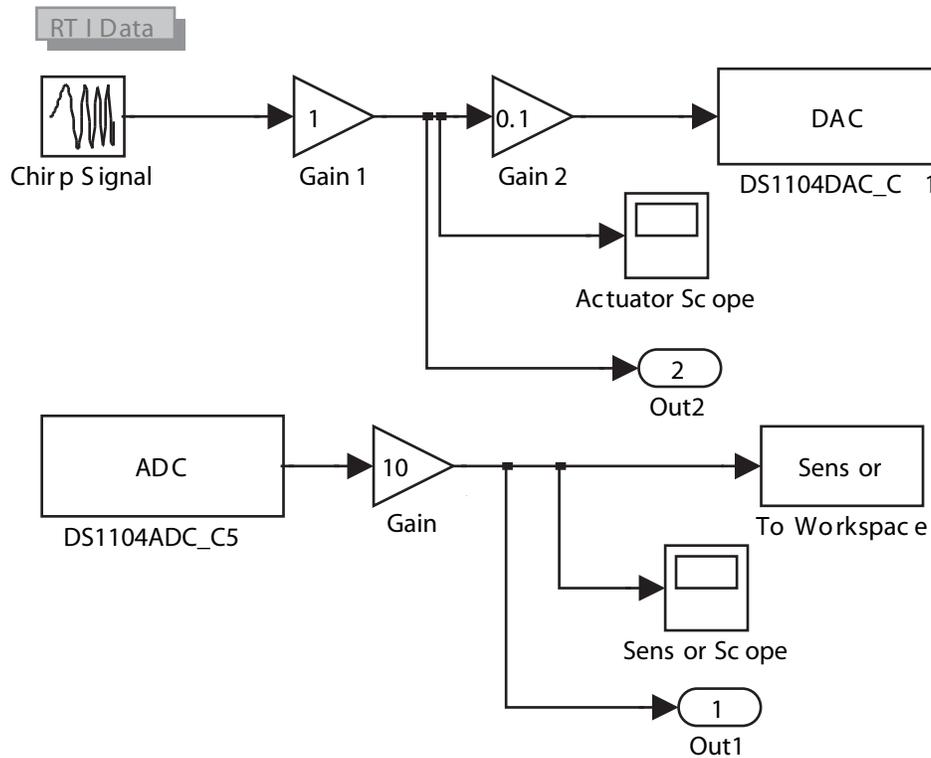
This experiment provides students with first-hand experience in observing, measuring, and experimentally determining a dynamics model for the piezoactuator. The experiment was implemented in a standard 3-hour lab period; likewise, each experiment described below was implemented in a 3-hour lab period.

An experimental system was designed for the laboratory activities and two examples are shown in Fig. 4. Both experiments consist of a bimorph piezoactuator, an inductive displacement sensor, a low-cost infrared sensor, a high-voltage amplifier (not shown) to drive the piezoactuator, and a PC with a data acquisition card (not shown).

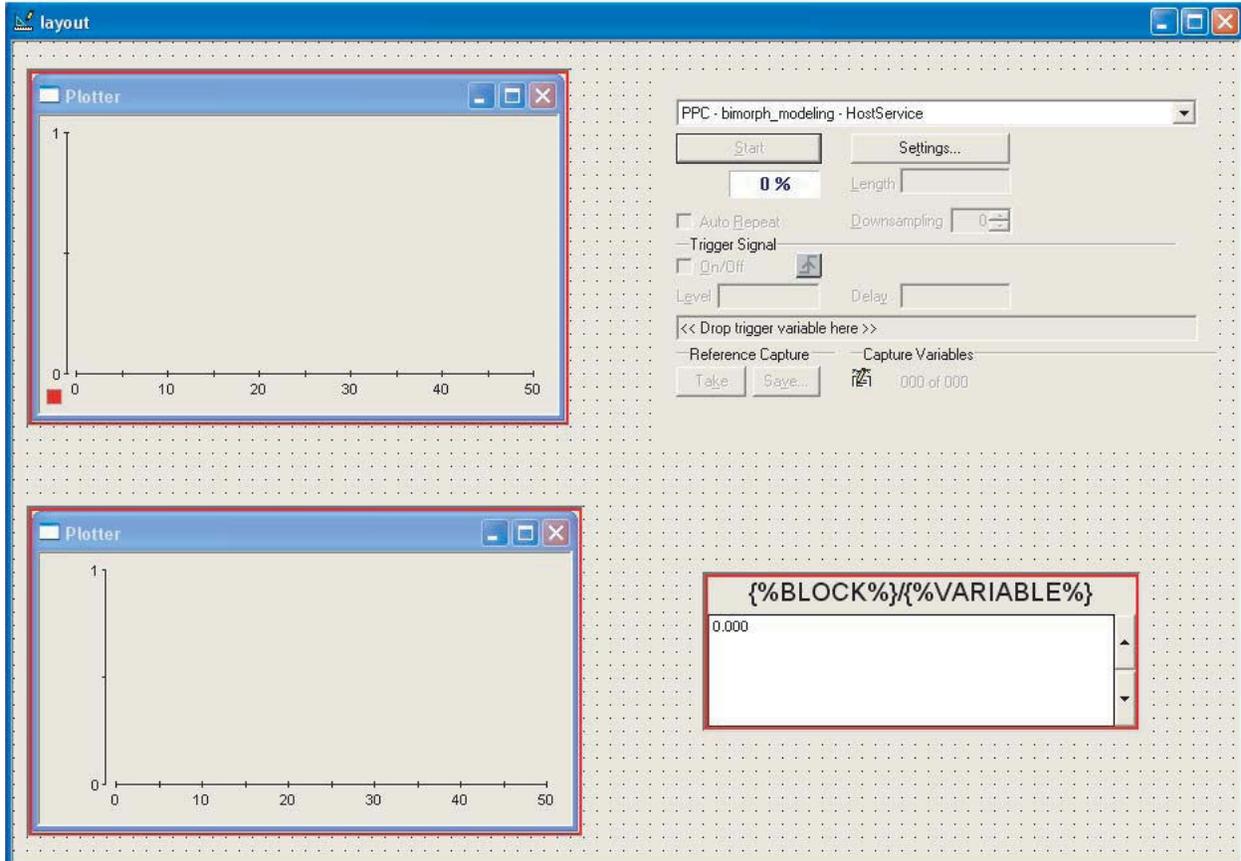
In this experiment, students modeled the linear vibrational dynamics using the swept-sine method, where the “industry-standard” Matlab software and a data acquisition card were used. First, students were asked to build a Simulink block diagram to implement the swept-sine method by using the Matlab command ‘chirp’. The command generates an appropriate input signal. Figure 5 shows one example of the Matlab Simulink model used for collecting data (with the DAQ card). Other types of DAQ systems can be implemented in a similar manner. Then, students were asked to apply the chirp input signal, followed by measuring the output response of the piezobimorph actuator. An example of the graphical user interface using dSPACE software is shown in Fig. 6. Next, students were asked to build a Matlab program (M-code) to process the measured input-output data to create the frequency response. The frequency response curves were then curve-fitted to obtain the transfer function model (6). An example frequency response and a transfer function model obtained by students are compared in Fig. 8. Finally, the step response was measured and recorded for post-processing and analysis. To further instill the modeling concept, post-lab work was given where students were asked to compare the transfer function model to the measured step response. An example Matlab program for this step is shown in Fig. 7.



**Figure 4.** Photographs of two modular piezoactuator experiments for laboratory activities. (a) The parts for this experimental platform were machined from Delrin plastic and aluminum. (b) The piezobimorph fixture was made using a rapid prototyping machine.



**Figure 5.** The Matlab-Simulink block diagram for measuring the frequency response of the piezobimorph actuator.



**Figure 6.** The graphical user interface of dSPACE for data acquisition.

### *Experiment EM2: Modeling Linear Vibrational Dynamics using Transient Response*

An alternative method to determine the numerical coefficients for the creep and vibrational dynamics model is to estimate them from the measured step response<sup>22</sup>. In this experiment, students were asked to measure the step response of the piezoactuator over two regimes: (1) over a long period of time (approximately 10 minutes) and (2) less than 500 ms. The coefficients for the creep model (5) were determined by curve fitting an exponential function to the transient response over the 10-minute period. The coefficients of the vibrational dynamics model (6) were found by estimating the percent overshoot, 2% settling time, rise time, and log-decrement value, then using these values to determine the damping ratio  $\zeta$  and natural frequency  $\omega_n$  for the standard second-order model<sup>22</sup>.

### *Experiment EM3: Measuring, Quantifying, and Modeling Hysteresis*

This experiment was designed to give students hands-on experience with measuring, quantifying, and modeling hysteresis in piezoactuators. Students were asked to build a Simulink diagram similar to the example shown in Fig. 5. The Simulink module was used to measure the input and output response of the experimental piezoactuator. The procedure asked students to apply a

triangle signal with different amplitudes to actuate the piezoactuator. Afterwards, they were asked to plot the measured output with respect to the applied input signal. The input versus output plots revealed hysteresis curves. From the curves, they were asked to quantify the amount of output hysteresis by simply calculating the difference between the measured output between the ascending and descending hysteresis curve. The calculated value was then compared to the range of the actuator, and typically the maximum measured hysteresis in the output varies between 10 and 20% of the range. Finally, students were asked to construct two simple models for hysteresis: a polynomial model (e.g., quadratic model) which related the input to the output signal; and a look-up-table model. These models can then be used to compensate for hysteresis behavior<sup>19, 23, 24</sup>.

```

% Step 1: Load in the measurement data;
a=load('wholespectrum');
wholespectrum=a.wholespectrum ;
output1=wholespectrum.Y(1).Data;
input1=wholespectrum.Y(2).Data;
% Step 2. Use the MATLABsystem identification
% toolbox to obtain the frequency response data;
zsw1 = iddata ( output1', input1', 0.0001 );
zswd1 = detrend ( zsw1 );
%specify the frequency range
f_range = ( 1 : 600 ) . * 2 * pi;
zf_sw1 = spafdr ( zswd1, [], f_range );
rd ( : , : ) = zf_sw1 ( 1 , 1 , : ).ResponseData;
freq = zf_sw1 ( 1 , 1 , : ).Frequency;
New_rd = interp1 ( freq, rd, f_range, 'linear' );
% Step 3. Use curve fitting method to obtain
% the transfer function model;
[ num, den ] = invfreqs ( New_rd, f_range,5,7);
My_TF = tf ( num, den );
% Obtain the simulated frequency response of the model;
My_FreqResp = freqs ( num, den, f_range );

```

**Figure 7.** An example of the main portion of the Matlab code for obtaining the transfer function model of the piezobimorph actuator.

**Figure 8.** The experimentally measured frequency response (‘experimental’) compared with the model response (‘fitted’), obtained by the students.

### Control of Piezoactuators

The application of piezoactuators requires the design of controllers that can account for hysteresis, creep, and vibration behavior. Feedback control, for example proportional-integral-derivative (PID), is standard in industry for controlling a multitude of dynamic systems such as robots, machining tools, and piezopositioners used in scanning probe microscopes. A set of lectures and laboratory experiments were developed to teach the fundamentals of feedback control, as well as introduce the concept of model-based feedforward control<sup>22</sup>. These instructional materials provided students with the theoretical foundation as well as hands-on skills for designing controllers for piezoactuators.

### *Lecture LC1: Notch Filter Design*

It has been recently shown that a challenge with applying feedback control to piezoactuators is the issue of low-gain margin inherent in these systems<sup>25</sup>. This is primarily due to low structural damping and the effects of additional dynamics. To address this issue, a lecture was developed to describe a simple method where a notch filter is added to improve the gain margin of a piezoactuator. The notch filter simply includes two zeros which cancels the effect of the two resonant modes of the system model Eq.(6). The notch filter is

$$D(s) = k_D \frac{(s - z_1)(s - z_2)}{(s - p_1)(s - p_2)}, \quad (7)$$

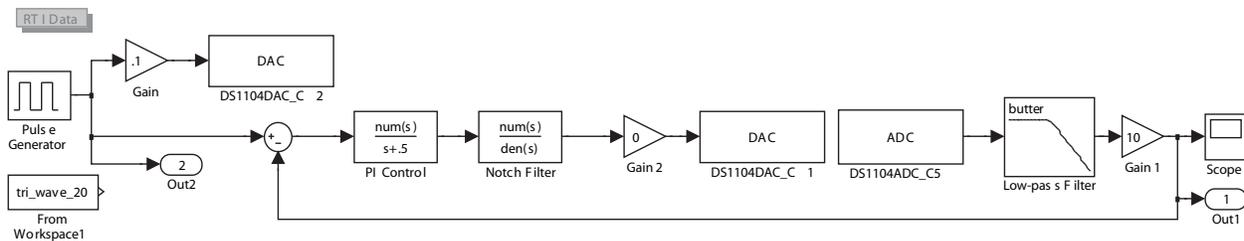
where  $k_D$  is the filter gain and the zeros and poles are given by  $z_i$  and  $p_i$ . The pair of poles at  $p_1$  and  $p_2$  is used to make  $D(s)$  proper, and they help attenuate high frequency noise. To illustrate gain margin improvement, an example Matlab program was presented which compares the gain margin of the original open-loop system with the notch filter and the open-loop system using the function ‘margin’. The improvement is typically over 20 dB. The notch filter can be made using analog op-amp circuits<sup>26</sup> and an example circuit was presented in the lecture. Students were also reminded the connection between the gain margin and the closed-loop stability, key concepts in feedback control design.

### Lecture LC2: Feedback Control

This lecture focused on designing traditional feedback controllers such as a proportional-integral (PI), proportional-derivative (PD), lead-lag, and PID for piezoactuators. For the PI, PD, and PID discussion, the following controller transfer function was described

$$C(s) = \frac{u(s)}{e(s)} = k_p + k_d s + \frac{k_i}{s}, \quad (8)$$

where the proportional, derivative, and integral gains are  $k_p$ ,  $k_d$ , and  $k_i$ , respectively. For each controller, a Matlab simulation example was shown in class (see Fig. 9), and students were reminded that PI control is typically used to achieve zero steady-state error; PD control dampens the output response; and PID combines the benefits of both methods.

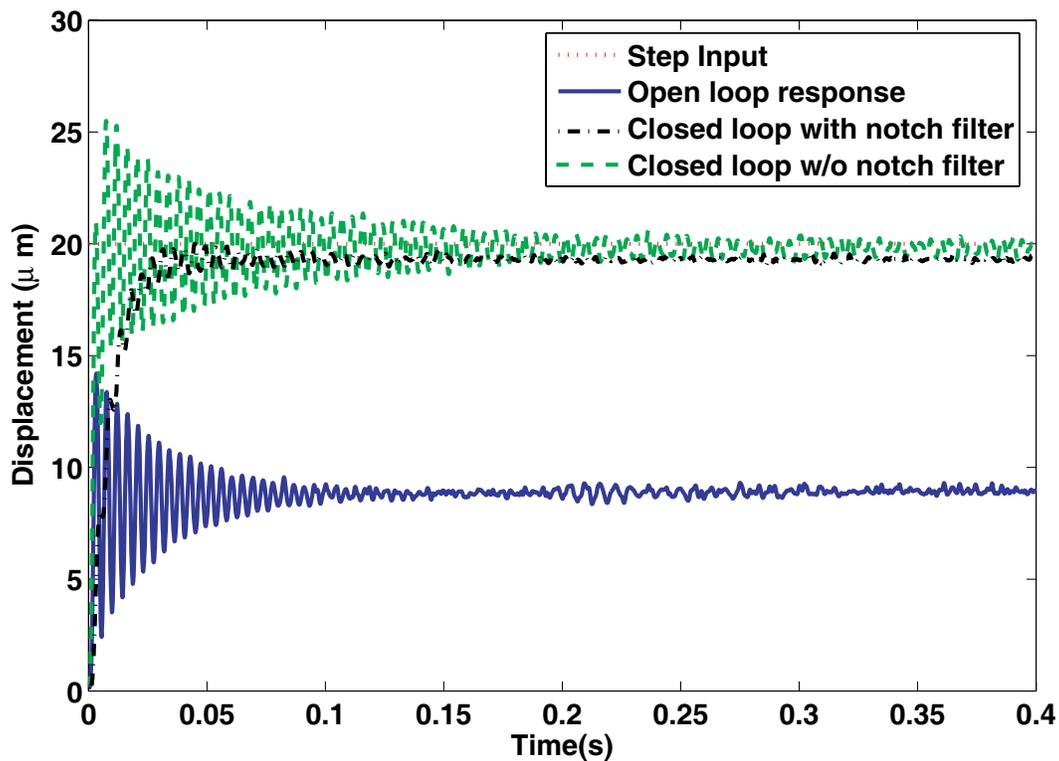


**Figure 9.** A Matlab-Simulink diagram of the feedback control for the piezobimorph actuator using a notch filter and a PI controller.

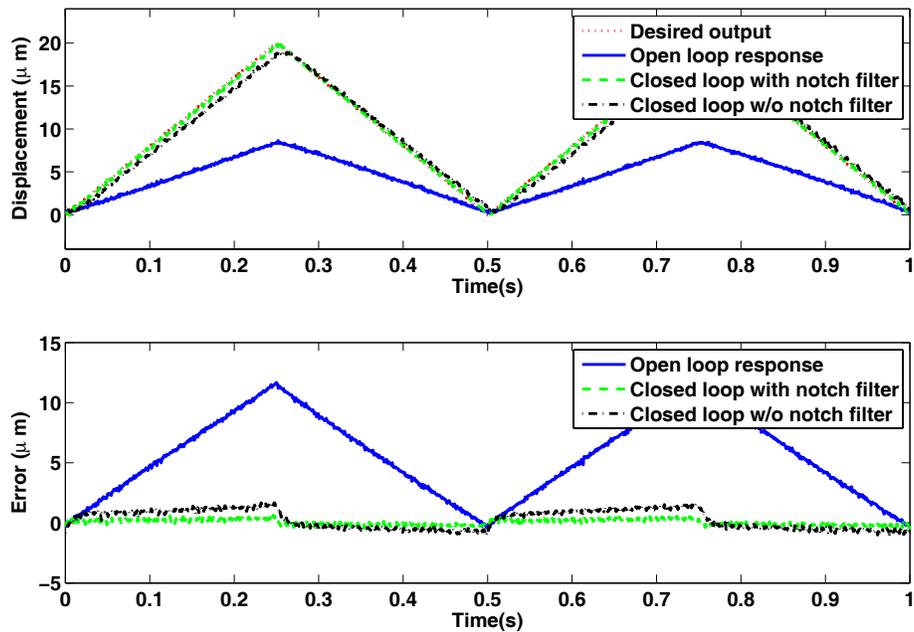
### Experiment EC1: Feedback Controller Design

This experiment follows the modeling Experiments EM1 and EM2, where students use the vibrational dynamics model obtain from those experiments to design a feedback controller. To enable the use of feedback control, they were first asked to design the notch filter  $D(s)$  discussed above. The design involved tuning the parameters of the notch filter using Matlab and comparing

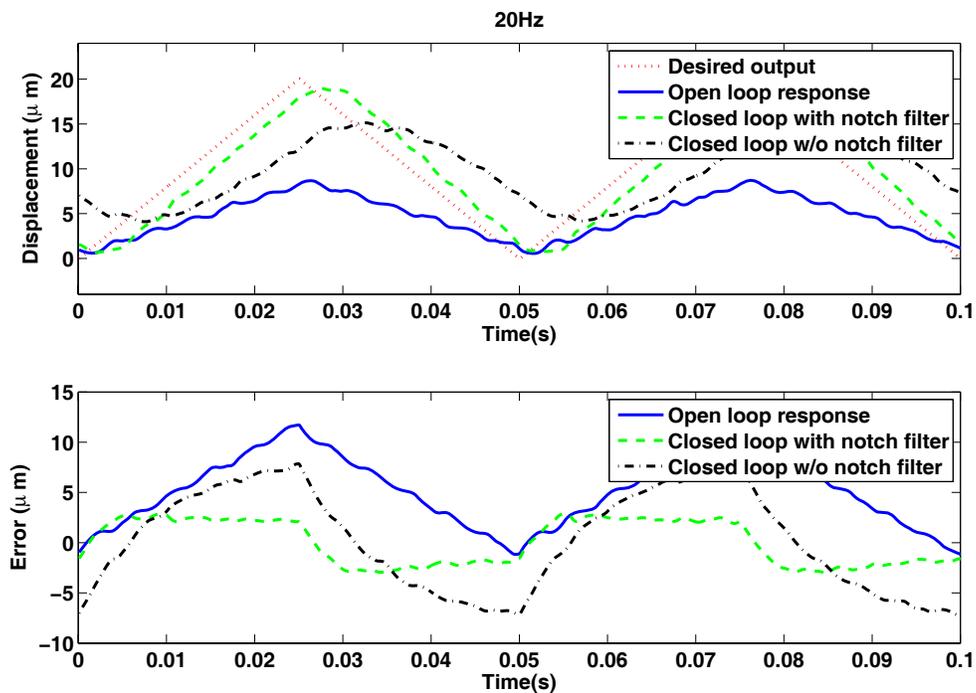
the gain margin before and after by analyzing the measured frequency response. Finally, they were given the task of designing a feedback controller of their choice to improve the transient and steady-state response of the piezoactuator. The design objective was to reduce the settling time by at least 70% and to minimize the steady-state error due to a step input. One example step response obtained by the students is shown in Fig.10, and it compares the uncompensated result with the controller response. Students were also asked to evaluate their design by observing and measuring the performance of tracking a triangle trajectory at both low-speed (2 Hz) and high speed (20 Hz). An example result is illustrated in Figs.11 and 12 (for 2 Hz and 20 Hz tracking, respectively). The comparison allows students to see the limitations of the feedback controller when the scanning speed increases.



**Figure 10.** Example results for the feedback control experiment. The plot compares the step responses of the open-loop and closed-loop system.



**Figure 11.** A comparison of the tracking responses of a triangle trajectory at 2 Hz.



**Figure 12.** A comparison of the tracking responses of a high-speed (20 Hz) triangle trajectory obtained by using (1) a notch filter and a lag-compensator; (2) only a lag-compensator; and the open-loop step response.

### *Experiment EC2: Hysteresis Control using Look-Up-Table Model*

This experiment uses the hysteresis model obtained from Experiment EM3 above to compensate for hysteresis behavior. To do this, the input versus output measurements were inverted such that for a given desired output value, a corresponding input value was found by using a look-up-table with the input versus output data and interpolation. This input was then applied to the piezoactuator, and the resulting output is the desired output value. This is a simple example of model-based feedforward control to address hysteresis-caused positioning error in piezoactuators.

### **Module Implementation**

The lecture and laboratory materials described above were developed at ISU and VCU. Recently, a pilot-implementation was done using the developed materials in three courses related to dynamics and control at these two schools. The courses included the junior-level Process and System Dynamics course (PSD), the senior-level Mechatronics course, and the senior-level Automatic Control course.

At VCU, the Process and System Dynamics course contained 66 students and the Mechatronics course contained 79. The PSD course focused on modeling and analysis of dynamic systems with no laboratory component. In PSD, Lectures LM1, LM2, and LM3 were delivered shortly after the treatment of mechanical and electrical systems modeling. A group project on modeling the experimental piezobimorph experiment was assigned in that same class to give students hands-on experience with modeling the piezoactuator. In the Mechatronics course, Lectures LC1 and LC2 were implemented during the semester the course was taught. This course consisted of a weekly lab where students spent 3 hours per week working on lab experiments. In Mechatronics, Experiments EM1 and EM2 were incorporated into the twelfth-week of instruction, shortly after the lectures on piezoactuators were presented.

At ISU, the materials were tested in the technical-elective automatic control course containing 9 students. (This course usually contains 10 to 20 students). The course focused on classical control theory. The laboratory components are a crucial part of the course. Students were grouped pairs and they worked on 6 experiments throughout the semester, and each experiment ran two weeks with two hours laboratory time per week. The experiments covered dynamics modeling, notch-filter design and implementation, and classical lead-lag, PID controller design and implementation, as described above. The experiments were synchronized with the lecture discussions to strengthen students' understanding and ability to link theory with real-world application. Lecture materials LM2, LC1, and LC2, and experiment materials EM1, EM2, and EC1 were incorporated into this course.

The design component was implemented at UW in a senior capstone design course, where several student-design teams used piezoactuators, as well as shape memory alloy actuators (SMA), in their design project. For example, one team designed an SMA-based robot and other group focused on designing a piezo-based nano positioning system.

## Preliminary Assessment Results

Both formative and summative assessments were implemented as a means of gauging student response to the instructional modules and in order to provide information to course instructors to guide modifications of the modules. Questionnaires were administered to students at the three schools on four separate occasions across the semester – beginning of the semester, immediately prior to the implementation of the teaching module, immediately following the end of the instructional module, and at the end of the semester. The questionnaires asked students about general content knowledge, as well as their perceptions about the importance and usefulness of nano and bio technologies involving smart actuators. In addition, students' homework, project and exam scores were recorded as summative data to investigate the impact of the modules on student learning/achievement. Finally, focus groups were conducted with students at VCU in order to gain additional insight and feedback regarding students' perceptions of the instructional modules. All assessment procedures followed IRB protocol to ensure participant anonymity and confidentiality.

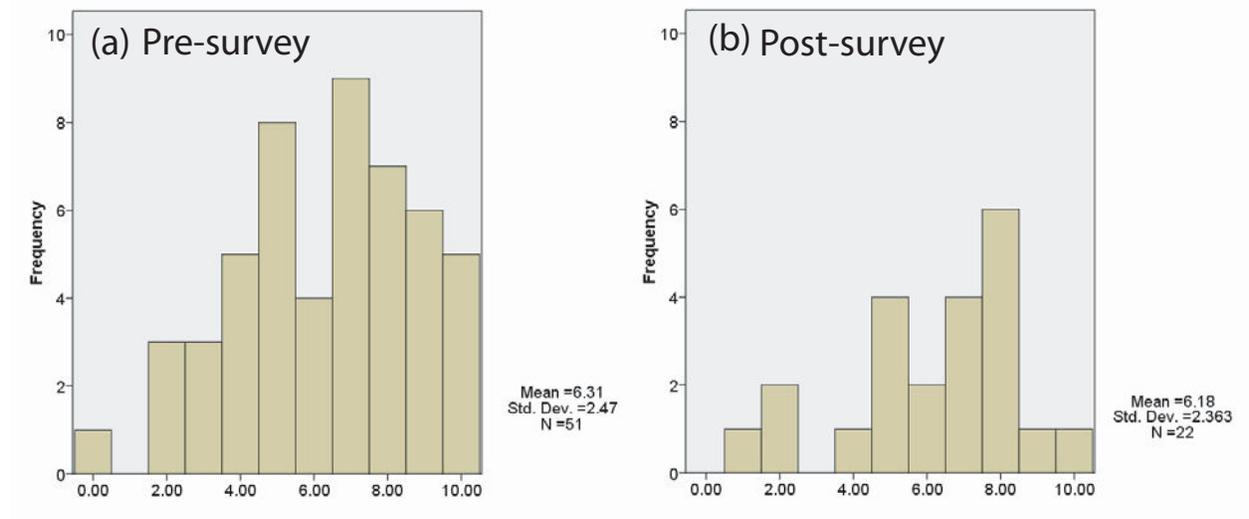
Preliminary results from pre-post module questionnaires and focus groups at VCU are reported. In total, 51 students completed pre-module questionnaires, while 22 students completed post-module questionnaires.

First, students were asked to rate their general level of excitement about nanotechnology-related fields on a scale of 1 to 10 with 10 being the most excited. Figure 13 shows a comparison of students' responses prior to and after the modeling and laboratory components were implemented. Overall, students were moderately excited about nanotechnology at both pre-test (Mean = 6.31, STD = 2.47) and post-test (Mean = 6.18; STD = 2.36). Interestingly, both pre-and post-questionnaire responses show multi-modal distributions, suggesting there may be separate sub-groups of students with lower and higher levels of excitement. While there were no substantial changes in students' level of excitement after being exposed to the instructional materials, this may be due to the fact that far fewer students completed the post-survey; and there was no way to link individual students' pre- and post-questionnaire responses. Future analyses will include greater examination of what may influence students' level of excitement because pre-and post-questionnaire responses will be linked with homework, project, and exam scores which will allow for direct comparisons across the semester.

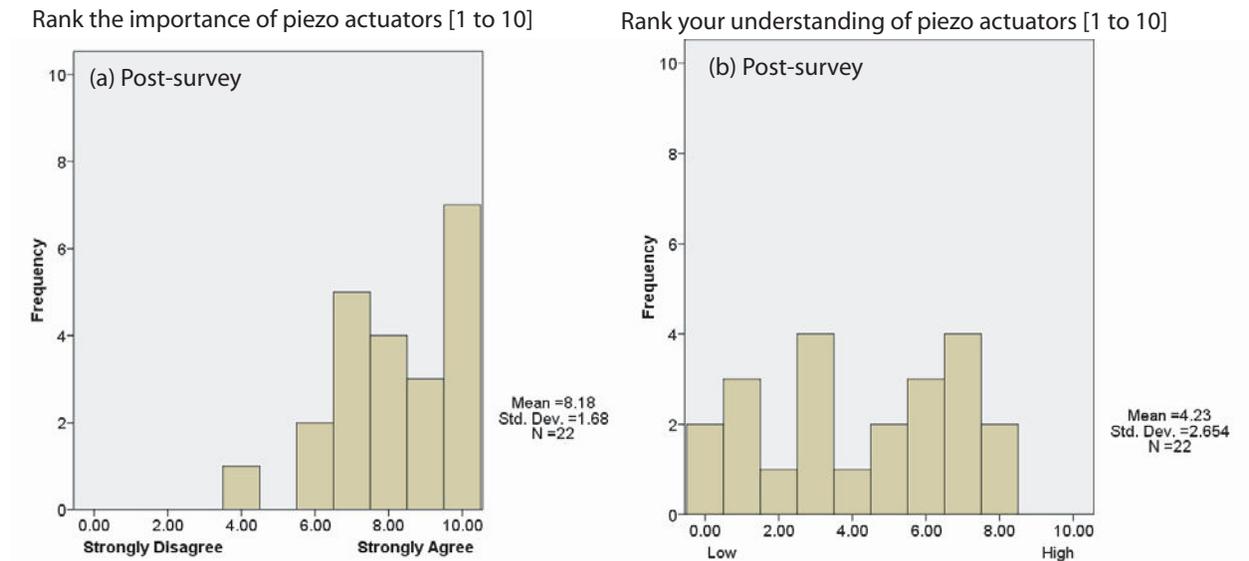
On the post-module questionnaire, students were asked to rate how important they believed piezoactuators to be in nano and bio technology on a scale of 1 to 10, with 10 being extremely important. The majority of students (81.9%) rated this item at 7 or higher with a mean of 8.18 and a STD of 1.68, identifying that they felt that piezoactuators were very important (Fig. 14a). When students were asked to rank their understanding of piezoactuators on a scale of 1 to 10, the graph in Fig. 14(b) shows a degree of variability in students' responses, again with somewhat distinct groups of students who rated their understanding as "low" or "moderate" (mean = 4.23; STD = 2.65). However, it is interesting to note that approximately 27.0% of students indicated they believed they had a moderately high (7 or 8 out of 10) understanding. Given that this question was not asked at pre-test, at this time it is impossible to evaluate if the module had a direct impact on students' responses to this particular item. The broad variability in students' responses might be related to the fact that this was many students' initial exposure to the

material. For example, upon completing the module students may have realized that the amount of material covered represents only a small amount of what could be learned about the subject matter.

### Self evaluation: How excited are you about nanotechnology?

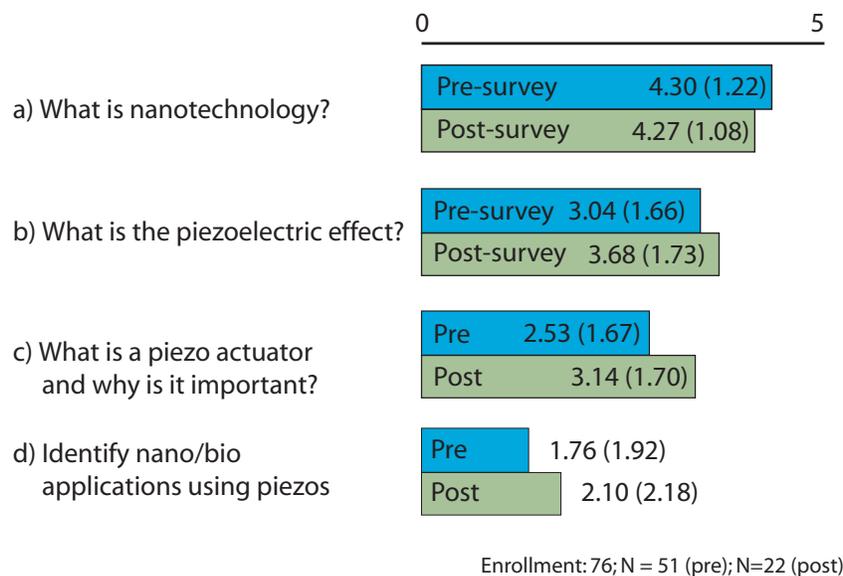


**Figure 13.** Pre- and post-survey results from students' self-evaluation of their level of excitement about nanotechnology: scale 1 to 10, with 10 being the most excited about the topic.



**Figure 14.** Post-survey results from students' perception of (a) the importance of piezoactuator in nano and bio technology and (b) their own understanding of the material, scale 1 to 10, with 10 being the greatest amount of understanding.

Finally, students were asked four specific questions to gauge their understanding of basic content related to nanotechnology and piezoactuators at both pre- and post-test. Figure 15 shows a comparison of students' responses with regard to their understanding of: nanotechnology, the piezoelectric effect, piezoactuators, and applications in nano/bio technology that use piezoactuators. Interestingly, the majority of students were able to describe nanotechnology regardless of being exposed to the teaching components that provided various examples of nano- and bio-related applications. On average, students earned scores of 4.27 (pre-survey) and 4.30 (post-survey) out of 5.0 possible points for this item. For each of the other three items, the average score for students who completed the post-survey was higher than the average score for students who completed the pre-survey. In general, students scores were approximately 0.25 to 0.64 points higher (based on a scale of 0 to 5 points). Students who completed the post-survey demonstrated somewhat greater understanding than students who completed the pre-survey of the piezoelectric effect (post-mean = 3.68, pre-mean = 3.04) and the importance of piezoactuators (post-mean = 3.14, pre-mean = 2.53).



**Figure 15.** Pre- and post-survey results and comparisons.

In general, preliminary results suggest that student learning and perceptions were positively impacted by the developed lecture and laboratory components. However, these results need to be interpreted cautiously as we have not assessed change in understanding at this time, but expect to do so with additional data currently being collected.

At VCU a total of six students participated in voluntary focus groups and provided additional information regarding their perceptions of the lecture and laboratory components that were developed. Overall, with the exception of one student, most students expressed that this was their first formal experience with this material; and that prior to this they had encountered topics related to nano and bio technologies primarily through their own independent reading or investigation. Students echoed students' responses on the questionnaires, commenting that they

found the material “very interesting” and were “excited” to learn more and broaden their understanding of applications related to piezoactuators. In terms of the lecture and laboratory materials themselves, students suggested that having the opportunity to “spend more time” and get “more information” in “greater depth” would be extremely useful. Participants indicated that having additional opportunities to “play with the technology,” and “have visuals to see how it works” in combination with substantive feedback on their assignments would greatly enhance their learning. Students also expressed an interest in being provided with additional information regarding the materials themselves, what they cost, where they can be purchased or accessed. Finally, students suggested that given how new and rapidly expanding this area is both in terms of application and research, providing an introduction earlier in the program would increase student interest, as would advanced topics seminars devoted to this material.

### **Benefits and Challenges**

One of the benefits of this project is the collaboration which enabled the sharing of ideas on how to best develop the module, its contents and how to implement them. Additionally, it allowed the distribution of work, and in the end a library of teaching materials was created with teamwork. Some challenges include finding ways to streamline the content so that it can be easily integrated into a course without it affecting other material that needs to be taught. The other challenge is the training of laboratory TAs to be proficient in conducting the lab. This process requires time and patient mentoring by the faculty member. Additionally, because the laboratory experiments were custom-made for this project, one foreseeable challenge is creating enough experimental systems at the reasonable cost to support a larger student population and for sustainability.

### **Conclusions**

This paper focused on the development and implementation of a teaching module on modeling and control of piezoactuator. Collaborators from three universities came together to create lecture and laboratory components. The developed teaching materials were recently implemented and preliminary survey results were presented. In general, the results suggested that student learning and perceptions were positively impacted by the developed teaching materials.

### **Acknowledgement**

Authors gratefully acknowledge the support of National Science Foundation DUE Grant #0633098.

## Bibliography

1. National Nanotechnology Initiative. Investment mode 2: NNI grand challenge areas. Technical report, 2004.
2. M. C. Roco and W. S. Bainbridge. Societal implications of nanoscience and nanotechnology. Technical report, National Science Foundation, 2001.
3. M. C. Roco. Broader societal issues of nanotechnology. *J. Nanoparticle Res.*, 5:181–189, 2003.
4. R. Wiesendanger. Scanning probe microscopy and spectroscopy. Cambridge University Press, Cambridge, 1994.
5. J.-H. Park, K. Yoshida, and S. Yokota. A piezoelectric micropump using resonance drive: proposal of resonance drive and basic experiments on pump characteristics. In *Proc. of the 1997 ASME Inter. Mech. Eng. Congress and Exposition: The Fluid Power and Systems Technology Division*, volume 4, pages 77–82, Dallas, TX, 1997.
6. J. M. Stevens and G. D. Buckner. Actuation and control strategies for miniature robotic surgical systems. *ASME Journal of Dynamic Systems, Measurement, and Control*, 127:537 – 549, 2005.
7. W. J. Palm. System dynamics. McGraw Hill, Boston, 2005.
8. D. G. Alciatore and M. B. Hiestand. Introduction to mechatronics and measurement systems. McGraw Hill, Boston, 2nd edition, 2003.
9. Q. Zou, K. K. Leang, E. Sadoun, M. J. Reed, and S. Devasia. Control issues in high-speed AFM for biological applications: collagen imaging example. *Asian Journal of Control*, 6(2):164–178, 2004.
10. W. P. Mason. Quartz crystals for electrical circuits. pages 11–56, New York, 1946. D. Van Nostrand Co., Inc.
11. A. Ballato. Piezoelectricity: history and new thrusts. In *IEEE Ultrasonics Symposium*, pages 575–583, 1996.
12. W. D. Callister. Materials science and engineering: an introduction. John Wiley and Sons, Inc., New York, 1994.
13. D. Croft, G. Shed, and S. Devasia. Creep, hysteresis, and vibration compensation for piezoactuators: atomic force microscopy application. *ASME J. Dyn. Syst., Meas., and Control*, 123:35–43, 2001.
14. K. Ogata. System dynamics. Prentice Hall, fourth edition, 2004.
15. L. E. Malvern. Introduction to the mechanics of a continuous medium. Prentice-Hall, Englewood Cliffs, NJ, 1969.
16. D. C. Jiles and D. L. Atherton. Theory of ferromagnetic hysteresis. *J. Magnetism and Magnetic Materials*, 61:48–60, 1986.
17. I. D. Mayergoyz. Mathematical models of hysteresis. Springer-Verlag, New York, 1991.
18. R. C. Smith, S. Seelecke, M. Dapino, and Z. Ounaies. A unified framework for modeling hysteresis in ferroic materials. *Journal of the Mechanics and Physics of Solids*, 54:46 – 85, 2006.
19. P. Ge and M. Jouaneh. Tracking control of a piezoceramic actuator. *IEEE Trans. Contr. Syst. Tech.*, 4(3):209–216, 1996.
20. K. K. Leang and S. Devasia. Design of hysteresis-compensating iterative learning control for piezo positioners: application to atomic force microscopes. *Mechatronics*, 6(3-4):141 – 158, 2006.

21. R. C. Barrett and C. F. Quate. Optical scan-correction system applied to atomic force microscopy. *Rev. Sci. Instr.*, 62(6):1393–1399, 1991.
22. G. F. Franklin, J. D. Powell, and A. Emani-Naeini. *Feedback control of dynamic systems*. 5th edition, 2006.
23. J. F. Jorgensen, K. Carneiro, L. L. Madsen, and K. Conradsen. Hysteresis correction of scanning tunneling microscope images. *J. Vac. Sci. Technol. B*, 12(3):1702–1704, 1994.
24. K. Dirscherl, J. Garnaes, L. Nielsen, J. F. Jorgensen, and M. P. Sorensen. Modeling the hysteresis of a scanning probe microscope. *J. Vac. Sci. Technol. B*, 18(2):621–625, 2000.
25. K. K. Leang and S. Devasia. Feedback-linearized inverse feedforward for creep, hysteresis, and vibration compensation in AFM piezoactuators. *IEEE Trans. Contr. Syst. Tech.*, 5(5):927–935, 2007.
26. H. Y-F. Lam. *Analog and digital filters: design and realization*. Prentice-Hall, New York, 1979.