Teaching Modules on Modeling and Control of Piezoactuators for System Dynamics, Controls, and Mechatronics Courses

Kam K. Leang, Member, IEEE, Qingze Zou, and Gina Pannozzo

Abstract—Piezoelectric actuators (or piezoactuators) are known for their nanoresolution and high-speed positioning capabilities. Therefore, they are used in scanning probe microscopes and in the design of innovative surgical tools and biomedical devices. The expected growth of engineering jobs in the nano- and bio-related fields, in which piezoactuators will play a significant role, motivated the development of a suite of teaching modules (lecture and laboratory materials) for the undergraduate mechanical engineering (ME) curriculum that focus on modeling and precision control of piezoactuators. Four laboratory exercises were designed to provide students with hands-on experience in data acquisition, sensors, and controller implementation. The developed modules were implemented in three undergraduate courses. The hypothesis being tested is that students who interact with these modules will gain a better understanding of piezoactuators and their application in nanotechnology and biotechnology. Through linked pre- to post-module comparisons, it is shown that students did, in fact, experience a positive change in their knowledge and understanding of the material.

Index Terms—Dynamics and control, hysteresis, mechatronics, nanopositioning, nanotechnology, piezoactuators.

I. INTRODUCTION

A RECENT projection notes that millions of new jobs will be created in the nano and bio fields worldwide by 2015 [1]. The expected growth of such jobs suggests that adequate preparation and training of the future workforce are needed. One of the most prevalent devices used in emerging nano- and biotechnology are sensors and actuators made from piezoelectric materials [2]. These materials are often referred to as smart or active materials. The piezoelectric actuator (or piezoactuator), a solid-state device used for actuation, is important because of its ability to displace or move with nanometer resolution. This unique ability for fine displacement is exploited in atomic force microscopy (AFM), where a piezoactuator is used to position a tool relative to a sample’s surface for imaging, as well as object manipulation at the nanometer scale [3]. Likewise, piezoactuators are employed in the design of surgical tools for minimally invasive surgery [4]. Piezoelectric-based actuators and transducers play a critical role in nanosystems and biotechnology similar to the role the electric motor has in common macroscale systems such as automobiles, home appliances, and entertainment devices. Therefore, training and preparing the future workforce with the knowledge and skills to design and engineer piezo-based systems is important.

The fundamental concepts in modeling and control of electric motors are covered in popular textbooks such as [5] and [6]. The subject is also tightly woven into core mechanical engineering (ME) classes like system dynamics, controls, and mechatronics. However, the treatment of piezoactuators is not common in the current ME curriculum, nor is it standardized. Specifically, modeling and control of piezoactuators have not been systematically integrated into core ME courses. Therefore, student exposure to the fundamental concepts of piezoactuators is limited. The contribution of this paper is the development of teaching modules that focus on modeling and control of piezoactuators for the undergraduate ME curriculum. The objective is to integrate the subject matter systematically into core mechanical courses, where modules are designed as plug-in teaching units for system dynamics, controls, and mechatronics courses.

The development of teaching modules is preferred over creating a new course on the subject. One reason for this is that integrating a new course into an existing curriculum is challenging due to required department- and university-level approval. Additionally, new courses must be carefully designed to consider their impact on the overall curriculum, as well as satisfying existing accreditation standards such as those of the Accreditation Board for Engineering and Technology (ABET) [7]. Although a technical elective course can be created with fewer restrictions, such courses impact a smaller number of students compared to core courses. Rather than developing a new or technical elective course, proposed herein are teaching modules that can be integrated into applicable core courses where the study of the piezoactuator is relevant. Such courses include system dynamics, controls, and mechatronics. The integration of teaching modules into core courses helps to broaden participation and impact. Additionally, the modules can be tailored to meet the specific learning objectives of the course at hand.

Efforts to integrate emerging technologies into the engineering curriculum have been documented in the literature. In particular, embedded systems (i.e., microcontrollers) for mechatronics and controls courses are described in [8]. The use of microcontrollers for open-ended student design projects...
in robotics is described in [9]. Likewise, the hardware and software requirements for microcontroller education are examined in [10], and the alternatives to embedded systems for mechatronics are found in [11]. On the topic of smart materials, the development of a senior-level course is described in [12], which focuses on piezo- and pyroelectricity. The course was designed to address practical applications and a project was assigned. Likewise, the study of shape memory alloy (SMA) is introduced to first-year engineering students in [13]. In that example, a handful of demonstrations involving SMAs were developed and presented to students. A Web-based experiment for controlling a piezoactuator is described in [14]. Although previous works have considered the integration of emerging technologies such as smart materials into the ME curriculum, the concepts of modeling and control of smart materials has not been systematically developed and implemented.

In contrast to previously developed educational materials on smart or active materials, the focus herein is to develop modules on the piezoactuator for integration into core ME courses and to test the hypothesis that students who interact with these modules will gain a better understanding of piezoelectric devices and their application in nano- and biotechnology. In particular, the modules are developed to address the key concepts that include: 1) transducers; 2) linear dynamic effects; 3) nonlinearity; 4) frequency response; 5) feedback control; 6) feedforward control; and 7) experimental design and implementation. Table I shows the subject modules on modeling and control of piezoactuators that address these concepts.

II. INTRO TO PIEZOELECTRIC EFFECT AND APPLICATIONS

Before students were exposed to the details of modeling and control of piezoelectric devices, a brief overview (approximately 15 min) is provided to promote engagement and motivate learning the modules shown in Table I. The introduction begins with a description of the piezoactuator as a device made from piezoelectric material. It is pointed out that the material responds to an applied voltage by changing its dimensions. Conversely, when stress is applied to the material, it produces a measurable voltage across its electrodes. It is also emphasized that the former behavior is typically exploited for actuation and the latter is for sensing as well as for energy harvesting applications [15].

The applications of piezoactuators and their useful working range are illustrated via the diagram shown in Fig. 1. The diagram compares the operating range of electric motors to piezoactuators. Piezoactuators are primarily used in the positioning of objects at the 1-mm down to the subnanometer range. Applications include scanning probe microscopes, micromachining, microrobotics, and fine-positioning of optics. Fig. 1(b) shows a schematic of an AFM, where the sharp tip at the end of the micromachined cantilever is used to scratch letters on a polymer surface (left image). The AFM image demonstrates the ability for micro- and nanoscale machining where a piezoactuator positions a sharp tool tip for scratching the tiny letters “VCU” at the micrometer scale. Other applications of piezoelectric materials that are presented can be found in [16].

III. MODELING PIEZOELECTRIC EFFECTS

Three lectures on modeling the response of piezoelectric devices were developed and designed for a 1-h class period. The first lecture covers the piezoelectric effect, a behavior that enables piezoelectric materials to be used as actuators and sensors. The subsequent two lectures focus on the input-to-output behavior of piezoelectric materials. In this case, the input is the applied voltage and the output is the actuator’s displacement. The behaviors include creep, hysteresis, and vibrational dynamic effects [17].

A. The Piezoelectric Effect and Constitutive Equations

The piezoelectric effect is presented by using the quartz crystal model first developed by Lord Kelvin in 1893 [18]. The simple 2D model is based on the unique characteristic of certain crystalline lattices that deform under pressure. The pressure induces separation of the centers of gravity of the positive and negative charges within the material creating
a dipole moment, which is the product of charge value and their separation. The resulting dipole moment produces an electric charge. This behavior explains the ability of piezoelectric material. Conversely, an applied voltage induces a mechanical strain in the crystalline lattice [18]. Fig. 2 shows the 2D model to illustrate the piezoelectric effect, where (a) represents the sensing and (b) represents the actuating ability of the piezoelectric material. The arrows next to the charges shown in the figure indicate the direction of motion of the charges. This discussion is also connected with concepts from physics and material engineering, e.g., the concept of charged particles and the crystalline structure of materials such as ceramics [19].

Next, the linear constitutive relationship describing the electromechanical properties of the piezoelectric material is presented. This discussion begins with Hooke’s Law relating the strain ($\delta$) to the compliance ($c$) and stress ($\sigma$) for everyday metals and plastics, $\delta = c \sigma$. Because piezoelectric materials have electrical properties, the basic constitutive equation for common dielectrics is included. The equation that relates the electric displacement ($D$) to the permittivity ($\epsilon$) and electric field ($E$) is given by $D = \epsilon E$. Combining these two basic constitutive equations, the following set of equations describe the electromechanical properties of the piezoelectric material:

\begin{align}
\delta &= \epsilon E \sigma + d^T E \\
D &= \sigma \epsilon + \epsilon E.
\end{align}

It is emphasized that (1) and (2) 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 [2]. Also, in order to describe or model piezoelectric materials, it is emphasized that one must have knowledge of the material’s mechanical properties (compliance or stiffness), its electrical properties (permittivity), and its piezoelectric coupling properties (piezoelectric modulus).

**B. Vibrational Dynamics and Creep Effect**

When voltage is applied to a piezoactuator, it displaces and exhibits the combined effects of hysteresis, creep, and vibration. These three effects are coupled, and the degree by which they appear in the output response depends on the input frequency and the range of motion. The approach to model the three effects is to decouple them into two main components: a hysteresis element (input nonlinearity) cascaded with a linear dynamics element that captures the creep and vibration effects [20]. The block diagram of the decoupled model in the frequency domain is illustrated in Fig. 3(a).

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 as the resonant modes of the actuator are excited. On the other hand, when a piezoactuator operates over long periods of time, creep becomes significant. Several combinations of these behaviors are depicted in Fig. 3 and discussed in the lecture.

The creep and vibrational dynamics are modeled using the lumped-parameter method and transfer function (Laplace domain) technique. It has been shown that the creep and vibrational dynamics effects can be modeled by a mass-spring-damper system. This approach is described in class, and the method goes hand-in-hand with key concepts in modeling mechanical systems in the ME undergraduate curriculum [6]. Likewise, the behavior of the spring-mass-damper system is connected with the vibrational modes of mechanical systems [21]. The transfer function model for the creep effect in terms of the spring and damper elements is given by [17] and [22]

\[ G_{\text{creep}}(s) \triangleq \frac{y(s)}{v(s)} = \frac{1}{k_i} + \sum_{i=1}^{N} \frac{1}{s c_i + k_i}, \]

where $k_i$ and $c_i$ are the spring and damper constants, respectively (see Fig. 4). Similarly, a simplified model of the vibrational dynamics is obtained by performing a force balance on a standard spring-mass-damper system. The transfer function model is

\[ G_{\text{vib}}(s) \triangleq \frac{y(s)}{v(s)} = \frac{\alpha}{s^2 + \left(\frac{m}{c}\right)s + \frac{k}{m}}, \]

where $m$, $c$, $k$, are the effective mass, damping, and spring constant of a piezoactuator, and $\alpha$ is a constant that relates the applied input voltage and force generated by a piezoactuator (assumed to be linear). Both models are derived in the lecture. Using these models, students are asked to simulate the creep and dynamics behaviors in Matlab through a homework assignment where the coefficients are taken from [23]. Additionally, an assignment is given to investigate the piezo’s response to slow time-varying signals (creep behavior) as well as to rapid signals like a step, ramp, and triangle input at different timescales. The homework exercise gives students the opportunity to study independently and to identify the slow drift effect caused by creep and the oscillations in the output due to the vibrational dynamics at high frequency.
C. Hysteresis Effect

Unlike the electric motor, a piezoactuator’s response shows hysteresis. This effect is also present in other active (or smart) materials such as shape memory alloys [24]. To teach the fundamentals of hysteresis, it is first emphasized that the behavior is nonlinear and the effect depends on the input magnitude [25], in contrast to linear systems in which the output magnitude scales proportionally with the input. Next, it is explained that the nonlinearity is attributed to the energy loss caused by microscale domain wall interactions within the material [26]. The discussion also draws an analogy with plastic deformation in materials [19]. The basic properties of hysteresis such as the local memory property and rate- and range-independency [27] are emphasized. Finally, various methods to quantify and characterize the hysteresis behavior, such as recording the maximum output variation relative to a linear behavior, are described.

IV. FEEDBACK AND FEEDFORWARD CONTROL

The following lecture modules focus on teaching control techniques for precision-positioning with piezoactuators. The modules emphasize the fundamentals of feedback [28], [29] and feedforward [17], [30] control techniques (see Fig. 5) for piezoactuators.

A. Challenges With Positioning With Piezoactuators

Piezoactuators are widely used in the design of high-precision positioning systems. It is emphasized that obtaining accurate models and implementing effective control strategies enable successful application of piezoactuators [31]. Since these actuators exhibit nonlinearity (i.e., hysteresis), accurate models can be difficult to obtain in practice. However, it is pointed out that a linear dynamics model, such as the second-order transfer function model typically used to describe the dynamics of a dc motor, can effectively model the dynamics of a piezoactuator over a small range (< 10% of total range). Such linear models can be used to design effective controllers for piezo systems with good performance.

Tracking error caused by vibrational dynamics, hysteresis, and creep effects are emphasized as major challenges. Although advanced control techniques have been proposed and effectively implemented (e.g., [17], [28], [31], and [32]), covering such topics is beyond the scope of the undergraduate curriculum. Instead, industry-standard feedback controllers including lead-lag and proportional-integral-derivative (PID) are taught using the piezoactuator as an example system.

B. Feedback Control Design for Piezoactuators

Application of feedback control for piezoactuators involves designing a notch filter to first improve system gain margin [20]. It is shown that a notch filter limits the magnitude of the input at specific frequencies to avoid exciting dominant modes and instability issues. With sufficient gain margin, the feedback gain can be increased to minimize hysteresis effect at low frequency without instability. A brief discussion is presented pointing out that low gain margin caused by the lightly damped vibrational modes (resonant peaks) as well as high-frequency dynamics can limit the performance of traditional PID control. Therefore, the basic idea of a notch filter is to use a pair of complex zeros, \( z_n, z_n^* \) (\( ^* \) denotes the complex conjugate), to cancel the resonant peak of the piezoactuator. For casual implementation, a
pair of complex poles, \( \{p_n, p_n^*\} \), is combined with the zeros. Finally, the notch filter transfer function \( G_N(s) \) is given by

\[
G_N(s) = k_d \frac{(s - z_n)(s - z_n^*)}{(s - p_n)(s - p_n^*)},
\]  

(5)

where \( k_d \) is the gain of the notch filter. To illustrate gain margin improvement, an example MATLAB program is presented that compares the gain margin of the original open-loop system with the notch filter cascaded with the open-loop system. The gain margin improvement can be over 20 dB (10 times). Finally, two practical methods to implement a notch filter are discussed: 1) the analog method using op-amp circuits [33]; and 2) the digital method using the MATLAB-Simulink environment.

The feedback controller with the notch filter, \( G_{FB}(s) \) (see Fig. 5(b)) is \( G_{FB}(s) = G_c(s) \times G_N(s) \), where \( G_c(s) \) denotes, for example, a standard lead-lag compensator or PID controller. This design has several benefits. First, since the notch filter enables high-gain feedback, at low frequency the hysteresis is minimized. Second, not only is the controller applicable to piezoactuators, but it can also be applied to other lightly damped dynamic systems such as flexible structures including cranes and robot manipulators.

Following the notch filter discussion, the classical lead-lag compensator is introduced. This discussion also includes PID-type controllers, which are widely used in industry for piezo-based systems. The lead-lag compensator \( G_c(s) \) has the following form:

\[
G_c(s) = k_c \frac{(s - z_l)(s - z_{ill})}{(s - p_l)(s - p_{ill})},
\]  

(6)

where \( k_c \) is the controller gain; \( \{z_{ll}, p_{ll}\} \) are the zero and pole of the lag compensator, respectively; and \( \{z_l, p_l\} \) are the zero and pole of the lead compensator, respectively. A PID controller is a special case of the above with transfer function

\[
G_c(s) = k_p + k_ds + \frac{k_i}{s},
\]  

(7)

where \( k_p, k_d, \) and \( k_i \) are the proportional, derivative, and integral gains, respectively.

To give students experience working with notch filters, a homework assignment is assigned asking them to compare the maximum controller gains, \( k_c \) in (6) and \( k_p \) in (7), for a feedback controller with and without a notch filter in the loop. The assignment also provides students the opportunity to investigate the role of the notch filter in controlling lightly-damped dynamic systems, which includes a flexible robotic arm and piezoactuator.

C. Feedforward Control for Hysteresis Compensation

Hysteresis effect is a complex nonlinear behavior, and without appropriate control (compensation), significant positioning error limits the performance of piezoactuators [20]. One approach to account for the hysteresis effect is feedforward control. This method involves modeling the hysteresis behavior and then using the model to compensate or anticipate for the hysteresis effect [see diagram in Fig. 5(a)]. The model is typically inverted to find an input for a given desired output behavior.

Several models for hysteresis are described, including the classic Preisach model, polynomial models, and simple lookup table models for feedforward control application [31]. The Preisach model consists of a sum of basic relays that represent, for example, the behavior of individual dipoles in the piezoelectric material [34]. This model is complex, and only the geometric interpretation is presented to show its basic properties.

The advantages of using feedforward control over feedback are discussed. In particular, with a reasonably accurate model, the performance can exceed that of feedback control because of feedforward’s ability to anticipate deficit performance. By inverting the linear dynamics, feedforward control can be used for vibration compensation to enable high-speed positioning [17]. One disadvantage of feedforward control is lack of robustness, especially when the system parameter changes (for example, due to aging or temperature effects) [35], [36].

V. LABORATORY MODULES

Experiments provide students with hands-on experience in observing, measuring, and controlling piezoactuators, thus preparing them for the practical aspects of emerging areas in nano- and biotechnology. The following laboratory modules are developed to enhance students’ understanding of the concepts in Fig. 1 and to complement the developed lecture modules.

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**Fig. 6.** Two modular piezoeactuator experiments for laboratory activities. (a) Setup machined from plastic and aluminum. (b) Setup made using a rapid prototyping machine.
A. Experimental Piezoactuator System

The two experimental systems shown in Fig. 6 were designed for the laboratory activities. Both experiments consist of a bimorph piezoactuator, an inductive displacement sensor (Kaman SMU0-9000-15N001), a low-cost infrared sensor (e.g., Fairchild QRB1113) [37], a high-voltage amplifier (not shown) to drive the piezoactuator, and a PC with a data acquisition card (not shown). The experimental setup in Fig. 6(b) is made by a rapid prototyping machine.

B. Prelab: Safety and High-Voltage Concerns

Piezoactuators are driven with high voltages; therefore, a short discussion to highlight certain safety issues is first presented before the students are allowed to work on their experiments. During the experiments, the instructor is required to check over students’ experimental setups before turning on the main power. In the event of an emergency, the students are instructed to inform the lab technician and instructor immediately.

C. Lab 1: Vibrational Dynamics and Creep Modeling Experiment

In this experiment, students model the linear vibrational dynamics using the swept-sine method, where a data acquisition card and the Matlab software are used to record and process the measured data. The experiment calls for students to do the following.

1. Build a Simulink block diagram to implement the swept-sine method using the Matlab command “verb1chirp1.” Fig. 7(a) and (b) show one example of the Matlab Simulink model used for collecting data (with the dSPACE DAQ card). Other types of DAQ systems can be implemented in a similar manner, such as Matlab’s xPC Target environment with National Instruments DAQ card.

2. Apply the chirp input signal while simultaneously measuring the output response of the piezobimorph actuator.
3. Write a Matlab program (M-code) to process the measured input and output data to create the frequency response.
4. Curve-fit the frequency response functions using the Matlab function “invfreqs” to obtain the transfer function model (4). An example of the frequency response and a transfer function model obtained for this step are compared in Fig. 8. The result shows good agreement.
5. Measure the step response of the piezobimorph for post-processing and analysis.

To instill the modeling concept further, post-lab work is given that asks students to compare the simulated step response of the transfer function model to the measured step response. An example of a Matlab program for this step is shown in Fig. 9.

D. Lab 2: Hysteresis Modeling Experiment

This experiment is designed to provide hands-on experience with measuring, quantifying, and modeling hysteresis in piezoactuators. The steps require students to do the following.

1. Build a Simulink diagram similar to the example shown in Fig. 7(a) and (b). The Simulink module is used to measure the input–output response of the experimental piezoactuator.
2. Apply a triangle signal with different amplitudes to actuate the piezoactuator and then measure the piezoactuator’s response.
Fig. 9. The main portion of an example Matlab code for obtaining the transfer function model of the piezobimorph actuator.

3. Plot the measured output with respect to the applied input signal (hysteresis curves).

4. Quantify the amount of output hysteresis by calculating the difference between the measured output between the ascending and descending hysteresis curves. The calculated value is then compared to the range of the actuator, and the maximum measured hysteresis in the output typically falls between 10% and 20% of the total displacement range.

5. Construct two simple models for hysteresis: a polynomial model (e.g., quadratic model by curve fitting) and a lookup table model that relates the input to the output signal. These models can then be used for feedforward hysteresis compensation [38], [39].

E. Lab 3: Feedback Control Design Experiment

The objective of this laboratory experiment is to teach the process of designing, simulating, implementing, and tuning a feedback controller for piezoactuators. The model of the dynamics obtained in Section V-C is used in this experiment. The procedures require students to do the following.

1. Design the notch filter $G_N(s)$ by following the above previous discussion (see Section IV-B). The design involves tuning the parameters of the notch filter using MATLAB, and comparing the gain margin before and after by analyzing the frequency response.

2. Design a feedback controller (PID, lead-lag, etc.) to improve the transient and steady-state response of the piezoactuator. The objective is to reduce the settling time (e.g., by over 70% reduction) and the steady-state error due to a step reference. An example of a Simulink block diagram and measured step response from student work are shown in Figs. 7(c) and 10, respectively. Note that in Fig. 7(c), the dSpace DAQ system (the blocks DS1104DAC_C 1 and DS1103ADC_CS in the figure) and the PI controller (PI Control block) are shown as examples. Also, a Butterworth low-pass filter (the block Low-pass Filter) is used to remove the measurement noise in the feedback loop, where the order of the filter is experimentally tuned.

3. Evaluate the design by observing and measuring the tracking results for a reference triangle trajectory at both low speed (2 Hz) and high speed (20 Hz). As shown in Fig. 11 for the 20-Hz case, the tracking performance is significantly improved by using the notch filter and a PI controller.
TABLE II
COURSES AND MODULES INVOLVED IN THE IMPLEMENTATION

<table>
<thead>
<tr>
<th>Course</th>
<th>Modules</th>
<th>Materials replaced/supplemented</th>
<th>Required time</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSD System dynamics</td>
<td>Piezo applications</td>
<td>Engineering examples</td>
<td>15 to 20 min. (1/2 lecture)</td>
</tr>
<tr>
<td>(Junior-level) Spring 07 &amp; 08</td>
<td>Physics of piezos</td>
<td>DC motor and electromech. sys</td>
<td>1 lecture</td>
</tr>
<tr>
<td></td>
<td>Modeling vib. &amp; creep</td>
<td>Spring-mass-damper systems</td>
<td>1 to 2 lectures</td>
</tr>
<tr>
<td></td>
<td>Project: Basic PID control</td>
<td>Intro to PID control</td>
<td>equival. to time required to complete 3 homeworks</td>
</tr>
<tr>
<td></td>
<td>design for piezoactuator</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mechatronics (Senior-level)</td>
<td>Hysteresis modeling</td>
<td>Nonlinearity</td>
<td>1 lecture</td>
</tr>
<tr>
<td>Fall 07</td>
<td>Feedforward control</td>
<td>Advanced control</td>
<td>1 to 2 lectures</td>
</tr>
<tr>
<td></td>
<td>Lab 1: Hysteresis modeling &amp;</td>
<td>Modeling &amp; control</td>
<td>2 to 3 hours lab</td>
</tr>
<tr>
<td></td>
<td>feedforward control</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lab 2: PID control + notch filter</td>
<td>Feedback control &amp; filter design</td>
<td>2 to 3 hours lab</td>
</tr>
<tr>
<td>Automatic Controls</td>
<td>Piezo applications</td>
<td>Engineering examples</td>
<td>15 to 20 min. (1/2 lecture)</td>
</tr>
<tr>
<td>(Senior-level) Fall 07</td>
<td>Modeling vib. &amp; creep</td>
<td>DC motor and electromech. sys</td>
<td>1 to 2 lectures</td>
</tr>
<tr>
<td></td>
<td>Lab 1: Modeling vib. &amp; creep</td>
<td>Experimental modeling</td>
<td>2 to 3 hours lab</td>
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<tr>
<td></td>
<td>Lab 2: PID feedback control</td>
<td>Feedback control design</td>
<td></td>
</tr>
<tr>
<td></td>
<td>design</td>
<td></td>
<td></td>
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</tbody>
</table>

F. Lab 4: Feedforward Control Design Experiment

This lab teaches a simple example of model-based feedforward control to address hysteresis-caused positioning error in piezoactuators. The experiment uses the hysteresis model obtained from the hysteresis modeling experiment discussed previously. First, the measured input-versus-output data is inverted (lookup table approach) such that for a given desired output value, a corresponding input value is found through interpolation. Then, the input is applied to the piezoactuator to compensate for the hysteresis effect. The uncompensated and compensated responses are measured and compared to evaluate the performance of the feedforward method.

VI. MODULE IMPLEMENTATION

The modules were implemented at Virginia Commonwealth University (VCU), Richmond, and Iowa State University (ISU), Ames. At VCU, the core courses involved were Process and System Dynamics (PSD, ENGR 315, Spring 2007 and 2008), a junior-level course on system dynamics and control, and Mechatronics (EGRM 410, Fall 2007), a senior-level course focusing on the integration of mechanical, electrical, and computer systems in design. The PSD course was a prerequisite to Mechatronics. At VCU, approximately 210 students were enrolled in the three classes. At ISU, several modules were implemented in the senior-level, technical elective course titled Automatic Controls (ME 411) during Fall 2007. In this course, 20 students were exposed to the teaching modules. Table II shows the modules implemented in each course, the materials either replaced or supplemented by the modules, and the approximate time required to present each module.

Because of limited instruction time, some standard course material was condensed to make room for the new material. For example, the dc motor is a commonly used example for describing the modeling of an electromechanical system. In this case, the dc motor is introduced in condensed form to make room for modeling the vibrational dynamics and creep effect of a piezoactuator in both the PSD and Automatic Controls class. The dc motor lecture is typically covered in two lectures, but it was condensed into one lecture period. Then, the modeling of the piezoactuator’s dynamic effects (vibration and creep) was presented in approximately two lectures, and analogies were drawn between the dc motor and piezoactuator.

The modules outlined in Table I can be implemented individually or as a group. For instance, the modeling modules 1–3 can all be presented to replace a traditional discussion on modeling of electromechanical systems such as dc motors in a system dynamics class, or one module (lecture or lab) can replace one specific topic to broaden a discussion or to bring in new technology into the classroom. However, it is recommended that an introduction to piezoactuators be presented prior to introducing any of the modules to provide a background and to motivate students to learn the new material (see Table II). Additionally, it is recommended that the control modules be presented after the modeling modules. If considered without the modeling modules, the instructor should ensure that students are familiar with basic concepts in system dynamics, such as Laplace transforms, transfer functions, and dynamics modeling.

Laboratory activities are an integral part of courses like mechatronics and automatic control. The developed laboratory experiments are primarily suited for such courses with a lab component. The laboratory modules listed in Table II were implemented starting the tenth week of the semester. Students were grouped into teams of four to work on each activity. One week after working on a lab activity, each team was required to submit a laboratory report describing what they learned and to explain their results.

VII. ASSESSMENT RESULTS

The impact of the modules was assessed for the PSD and Mechatronics course at VCU. The objective was to determine whether students gained a better understanding of piezoactuators and applications in nano- and biotechnology after inter-
TABLE III
PRE-/POST-MODULE ASSESSMENT RESULTS BY COURSE

<table>
<thead>
<tr>
<th>Item</th>
<th>PSD Spring 2007</th>
<th>Mechatronics Fall 2007</th>
<th>PSD Spring 2008</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre (SD) (n = 51)</td>
<td>Post (SD) (n = 22)</td>
<td>Pre (SD) (n = 48)</td>
<td>Post (SD) (n = 41)</td>
</tr>
<tr>
<td>1. What is nanotechnology?</td>
<td>4.29 (1.22)</td>
<td>4.27 (1.08)</td>
<td>2.46 (0.76)</td>
<td>2.53 (0.85)</td>
</tr>
<tr>
<td>2. What is the piezoelectric effect?</td>
<td>3.04 (1.66)</td>
<td>3.68 (1.73)</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>3. What is a piezoactuator? Why is it important?</td>
<td>2.53 (1.67)</td>
<td>3.14 (1.70)</td>
<td>2.54 (1.16)</td>
<td>2.60 (1.50)</td>
</tr>
<tr>
<td>4. Identify a nano and/or biotechnology that utilizes a piezoactuator.</td>
<td>1.76 (1.92)</td>
<td>2.09 (2.18)</td>
<td>2.11 (1.51)</td>
<td>3.15 (1.69)</td>
</tr>
<tr>
<td>5. What are the major issues with high precision control of piezoactuators?</td>
<td>--</td>
<td>--</td>
<td>1.77 (1.22)</td>
<td>3.45 (1.34)</td>
</tr>
</tbody>
</table>

acting with the modules. Of the 210 students who interacted with the modules during class time and in the laboratory at VCU, 95.0% consented to participate in the assessment. All assessment procedures followed IRB protocol to ensure participant anonymity and confidentiality. The results reported here come from three courses, PSD Spring 2007 and 2008 and Mechatronics Fall 2007. Because the modules were only implemented in one class at ISU with a relatively small number of students ($n = 20$) and the class was substantially different than the courses at VCU, those results are not discussed.

The assessment consisted of questionnaires and focus groups. Questionnaires were administered to students in PSD and Mechatronics on four separate occasions across the semester: beginning of the semester (first two weeks of instruction), immediately prior to the implementation of the teaching module (between weeks 4 and 10), immediately following the end of the instructional module, and at the end of the semester (last two weeks of instruction). Questionnaires include both open-ended and Likert-type items, and they were completed anonymously by students, with the exception of PSD Spring 2008 where linking of students’ pre- and post-module responses was done in order to determine if there had been changes in students’ knowledge. Questionnaire items asked students about their knowledge, understanding, and interest related to nano/biotechnology and piezoactuators. Open-ended items were scored for correctness with a possible point range of 0 to 5. Likert-type item responses ranged from 0 to 10, with increasing numbers indicating higher levels of interest or importance. Focus groups were conducted with students during the last three weeks of the semester in order to gain additional insight and feedback regarding students’ perceptions of the instructional modules.

The results of the premodule questionnaires were formative, and the post-module questionnaires were summative. Additional data collected included students’ homework, project, and exam scores (results omitted for brevity). These were used as summative measures to examine students’ learning of the content covered in the modules. The formative results were used to give a snapshot of students’ general understanding of the material to better prepare the delivery of the material. Across the implementation of the project, questionnaires and assessment procedures were revised to accommodate changes in the modules and strengthen the quality of the data collected.

The results of the open-ended questionnaire items (mean and standard deviation) by course are reported in Table III. A subset of the data from the PSD Spring 2008 ($n = 37$) linking students’ pre- and post-module responses is shown in Table IV. A subset of the total data (pre: $n = 46$ and post: $n = 41$; see Table III for PSD Spring 2008) was considered because 37 pre- and post-questionnaires were linkable through an identifier.

A. Questionnaire Results

The pre- and post-module questionnaires (Table III) included a series of five open-ended questions that asked specifically about nanotechnology and piezoactuators: 1) What is nanotechnology? 2) What is a piezoactuator, why is it important? 3) What is the piezoelectric effect? 4) Identify a nano and/or biotechnology that utilizes a piezoactuator; and 5) What are the major issues with high precision control of piezoactuators? 1 The post-module questionnaires also included the following three Likert-type items: 1) How important are piezoactuators? 2) How excited are you about nanotechnology? and 3) Rate your understanding of modeling of piezoactuators. Students were asked to rate their responses on a scale of either 0 to 10 or 0 to 5, with higher numbers indicating higher levels of importance, excitement, or perceived understanding.

As shown in Table III, the standard deviations suggest that there was a high degree of variability in students’ knowledge of

1Question 2 was administered to students in PSD only, while question 5 was only administered to students in Mechatronics.

2In PSD—Spring 2008, the wording of the items and response scales were revised slightly to provide better anchors for students’ responses.
nanotechnology (question 1) prior to the module implementation across the three classes. However, overall, students earned an average score of 2.90 \( (SD = 0.91) \) out of 5.0 points on this item, suggesting that prior to the modules students had a reasonable general knowledge of the topic. It is interesting to note that the Fall 2007 PSD class demonstrated a much stronger understanding in their responses on this item, earning an average score of 4.29 \( (SD = 1.22) \) when compared to students in Spring 2008 class \( (M = 1.96, SD = 0.76) \). A possible explanation is the instructor’s expectation of students’ understanding increases with the number of implementations, which impacts the scoring of the questionnaires.

Students in the PSD classes were asked to explain the piezoelectric effect as part of the pre- and post-module questionnaires (question 2 in Table III). Across the two classes, students earned an average of 2.27 \( (SD = 1.55) \) out of 5 points for their responses to this item before implementing the module. Afterward, the average increased to 3.33 \( (SD=1.58) \). Similarly, while students may be able to define nanotechnology generally, they have less knowledge of specific content related to piezoactuators at the premodule stage.

For questions 3 and 4, asking students to describe a piezoactuator and its importance and identifying applications that use piezoactuators, respectively, results across the three courses showed a notable increase in the average at post-module, from 2.17 to 2.94 for question 3 and 1.70 to 2.80 for question 4. Disaggregating the data by class shows no discernible pattern with regard to the three classes.

Finally, students in the Mechatronics class were asked about the major issues with high precision control of piezoactuators. Out of a possible 5 points, students earned an average of 1.77 \( (SD = 1.22) \) points at premodule, then 3.45 \( (SD = 1.34) \) at post-module. At premodule, this suggested that while students may be familiar with nanotechnology and piezoactuators, they had only limited knowledge of specific issues related to their use or control.

Following implementation of the modules, students were asked to rate the importance of piezoactuators and nanotechnology, their excitement about nanotechnology, their own understanding of the subject matter, and the usefulness of projects and homework to gaining an understanding of the material. The response to the Likert-type questionnaires indicated that students rated the importance of piezoactuators as relatively high, with 81.9\% of students selecting 7 out of 10 or higher for this item. These same students reported moderate average levels of excitement, 6.18, \( SD = 2.36 \). Students were somewhat more conservative in their ratings of their own understanding of the subject matter, the highest rating was 8 out of 10, with only 27.0\% responding 7 or higher. Finally, students were asked if the project and homework assignments helped them to develop a better understanding of piezoactuators. For this item, approximately 31.8\% of students strongly agreed or felt that the assignments were very helpful (a response of 7 or higher out of 10), with an average rating of 5.50, \( SD = 2.79 \).

The results between pre- and post-module questionnaires in Table III show differences in students’ responses to the open-ended questionnaire items. However, in the first two implementations of the modules (PSD Spring 2007 and Mechatronics Fall 2007), there was no mechanism for linking students’ pre- and post-module responses, so there was no way to determine if the same students answered both the pre- and post-module questionnaires. This made it difficult to determine if the higher scores on the post-module questionnaire items were due to changes in students’ knowledge or simply because a different subset of students with greater knowledge responded.

However, in the Spring 2008 PSD course, the assessment plan was modified to allow for linking of students’ pre- and post-module responses, in order to determine if there had been changes in students’ knowledge. As can be seen in Table III, the post-module means on all but the first question were higher than the pre-module means. A subset \( (n = 37) \) of the data from students who had complete the pre- and post-module responses were analyzed using t-tests to examine if the differences in scores from pre- to post-module were statistically significant. The results can be found in Table III. With the exception of ques-

### Table IV

<table>
<thead>
<tr>
<th>Item (n = 37)</th>
<th>Pre-Module Mean (SD)</th>
<th>Post-Module Mean (SD)</th>
<th>Mean Difference (SD)</th>
<th>t-statistic (df = 36)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. What is nanotechnology?</td>
<td>2.05 (0.74)</td>
<td>1.86 (0.75)</td>
<td>-0.19 (0.94)</td>
<td>-1.227</td>
</tr>
<tr>
<td>2. What is the piezoelectric effect?</td>
<td>1.68 (1.49)</td>
<td>3.11 (1.05)</td>
<td>1.49 (1.73)</td>
<td>5.149**</td>
</tr>
<tr>
<td>3. What is a piezoelectric actuator? Why is it important?</td>
<td>1.43 (1.46)</td>
<td>2.92 (1.48)</td>
<td>1.43 (1.69)</td>
<td>5.239**</td>
</tr>
<tr>
<td>4. Identify a nano and/or biotechnology that utilizes a piezoactuator.</td>
<td>1.27 (1.74)</td>
<td>3.11 (1.35)</td>
<td>1.84 (1.88)</td>
<td>5.951**</td>
</tr>
<tr>
<td>5. Rate your understanding of modeling of piezoactuators.</td>
<td>4.32 (0.88)</td>
<td>3.27 (0.96)</td>
<td>-1.05 (1.18)</td>
<td>-5.446**</td>
</tr>
</tbody>
</table>

**p < .01
tion 1 “What is nanotechnology?” there were statistically significant differences between scores on the pre- and post-module responses to the questionnaire items. Students scored significantly higher after the implementation of the module on the items asking students to explain what a piezoactuator is and why it is important ($t_{1,36} = 5.229, p < 0.01$), the piezoelectric effect ($t_{1,36} = 5.149, p < 0.01$), and identify a nano and/or biotechnology that utilizes a piezoactuator ($t_{1,36} = 5.951, p < 0.01$). For each of these items, the post-module mean was over 0.80 with a standard deviation higher than the premodule mean.

There was also a statistically significant difference between pre- and post-module responses for the item asking students to rate their own understanding of nanotechnology on a five-point scale ($t_{1,36} = -5.446, p < 0.01$). Interestingly, the average rating was higher before module implementation than it was after module implementation (4.32 versus 3.27, respectively). The mean difference represents an approximate 0.89 SD decline in students’ rating of their understanding of nanotechnology. While this may seem counter-intuitive, this result is often seen in projects of this type. Once individuals have the opportunity to engage with content that is unfamiliar, they often revise their perceptions of their understanding based on new information, which results in lower ratings post-intervention.

The pre- to post-module comparisons suggest that students did, in fact, experience a positive change in their knowledge and understanding of nanotechnology and piezoactuators. Students demonstrated a stronger understanding of piezoactuators, the piezoelectric effect, and had greater ability to identify a nano- or biotechnology that used piezoactuators after the modules had been implemented. A control group was not considered in this study, and the comparisons were thus limited to a single class. Therefore, it is impossible to attribute the positive changes in students’ scores directly to the implementation of the modules. For example, after being introduced to the content, students might have chosen to seek out additional information independently, which could also explain the significant results. However, the fact that there were positive changes suggests that the use of these modules to deliver nanotechnology and piezoactuator-related content to ME students might have some merit and warrants further investigation through broader implementation and evaluation.

B. Focus Groups

Ten students participated in voluntary focus groups and provided their perceptions about the developed lecture and laboratory components. With the exception of one student, all 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 biotechnologies primarily through their own independent reading or investigation. Echoing students’ responses on the questionnaires, students commented that they found the material “very interesting” and are “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 indicate 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, such as what they cost and 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 seminars on advanced topics devoted to this material.

C. Additional Considerations

One of the main challenges of implementing the modules was time. For example, the modeling modules involved several hour-long lectures that can be time-consuming. Without careful preparation, time can be taken away from covering other important course material. Also, students’ limited exposure to nonlinear systems posed a challenge when discussing the hysteresis behavior. The instructor found it difficult to keep students motivated in their learning and considers that this may be because students could not directly relate to hysteresis. As for the experiments, for a large class, a large number of experimental setups were required, which can be costly to both produce and maintain.

VIII. CONCLUSION

The development of lecture and laboratory teaching modules that focus on modeling and control of piezoactuators for the ME undergraduate curriculum was described. The modules were designed for dynamics and control courses as well as for mechatronics courses. The entire suite of modules can be used as a whole, or in part, to teach concepts such as dynamics modeling, electromechanical coupling, and feedback and feedforward control using the piezoactuator as an example system. An experimental piezoactuator platform was designed to give students hands-on experience in modeling and controlling piezoactuators for high-precision positioning applications. The teaching modules were implemented in one junior-level and two senior-level classes in system dynamics, control, and mechatronics. The t-test was used to test the hypothesis, and through linked pre- to post-module comparisons, assessment results indicated that students experienced a positive change in their knowledge and understanding of the material.

REFERENCES


[29] K. K. Leang (M’08) received the B.S. and M.S. degrees in mechanical engineering from the University of Utah, Salt Lake City, in 1997 and 1999, respectively, and the Ph.D. degree from the University of Washington, Seattle, in December 2004.

[30] He joined the Department of Mechanical Engineering, University of Nevada-Reno, in 2008. From 2005 to 2008, he taught in the Mechanical Engineering Department at Virginia Commonwealth University, Richmond. His research interests include modeling and control of piezoelectric hysteresis, high-speed imaging and broadband characterization of soft materials, fabrication and control of electroactive polymers, mechatronics, and design of microelectromechanical systems (MEMS) for nanotechnology.

Dr. Leang is a Member of ASME and SPIE.

[31] Qingze Zou received the B.S. degree in automatic control from the University of Electronic Science and Technology of China (UESTC), Chengdu, China, in 1994, the M.S. degree in mechanical engineering from Tsinghua University, Beijing, China, in 1997, and the Ph.D. degree in mechanical engineering from the University of Washington, Seattle, in 2003.

[32] He joined the Department of Mechanical Engineering, Iowa State University, Ames, as an Associate Professor in 2004. His primary research interests are in inversion-based output tracking theory, high-speed imaging and broadband characterization of soft materials using scanning probe microscopy (SPM), and high-throughput nanomanufacturing.

Dr. Zou is a recipient of the NSF CAREER Award in 2009. He is a Member of ASME.

[33] Gina Pannozzo received the B.A. degree in psychology from Binghamton University, State University of New York (SUNY), Binghamton, in 1991, and the M.A. and Ph.D. degrees in educational psychology from the University at Buffalo, SUNY, Buffalo, in 1994 and 2005, respectively.

[34] She joined the Foundations of Education Department, Virginia Commonwealth University, Richmond, in December 2004. Her research interests include student encouragement in school, classroom and school climate, culture and sense of community, and impact of small class size on students and teachers.