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Integrating Nanopositioner Design Issues into an Existing Automatic Controls Course through Homework*

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This article describes the integration of design aspects of nanopositioners into an undergraduate, Automatic Controls (AC) course in the Mechanical Engineering (ME) Department at the University of Washington (UW), Seattle. The course development is part of an overall effort to integrate nanotechnology into the undergraduate curriculum at UW through a mixture of new and existing courses. The current article addresses challenges in adding new content in existing courses (such as AC) by integrating nanopositioner design issues with concepts already taught in the course (such as control design to increase bandwidth), and the use of homework (HW) to allow students to explore the application of course concepts into the nanotechnology area. Learning assessment results are presented to demonstrate that students were well able to meet the learning objectives.

Keywords: nanotechnology; automatic control; piezoelectric devices; homework

1. Introduction

The growing need to build the human resource infrastructure for emerging nanotechnology industries has led to several initiatives on nanotechnology research and education [1–6]. The Mechanical Engineering (ME) academic community also has recognized that nanotechnology is a key 'thrust area' for ME research and education, e.g., [7]. This has led to an effort in the ME Department at the University of Washington (UW), Seattle, to develop nanotechnology-related material for the undergraduate ME curriculum [8]. The course development in automatic control (AC), described in this article, falls within this overall effort to integrate nanotechnology into the undergraduate curriculum at UW through a mixture of new and existing courses. AC tends to be a core course taught in many departments; therefore, although the article describes a course development in a ME Department, parts of the proposed approach to integrate nanopositioner design issues into existing AC courses are applicable to other Engineering Departments.

The interest in introducing nanotechnology topics into the AC course arises from the substantial role played by controls in nanotechnology, especially in nanopositioning applications [9, 10]. For example, nanopositioning systems are needed in scanning probe microscopes, which are key tools in investigation and manipulation of nanoscale biological, chemical, material, and physical processes [11, 12]. Moreover, nanopositioning systems are needed in the semiconductor industry for positioning of wafers, mask alignment, and inspection systems [13–15], and in high-density, data storage, e.g., [16]. In each of these wide-ranging applications, the use of AC techniques can improve the performance by increasing the bandwidth (operating speed) of nanopositioning systems [9]. Therefore, introducing nanopositioning issues into undergraduate AC courses can help prepare students to enter different areas of the nanotechnology field. Additionally, integrating applications (such as nanopositioning) into courses can enhance the learning of basic engineering concepts. This is because seeing the usefulness of what one is studying (e.g., through applications) enhances learning since humans are motivated to acquire such competence [17–20].

The novelty of the course development (described in this article) is the integration of design aspects of nanopositioners into an undergraduate, AC course. The new material in the AC course aims to: (i) illustrate the importance of range (the maximum achievable position) and bandwidth (the maximum achievable positioning frequency with sufficiently-low positioning error) in the design of nanopositioners; (ii) show that the maximum bandwidth (of typical nanopositioners) is limited by the range requirement, (iii) quantify the improvement in bandwidth (for a fixed range) that can be achieved by using different AC designs; and (iv) explore novel (non-control-based) design strategies to overcome such limits on the achievable bandwidth. By focusing on the range-bandwidth tradeoff, the current course development integrates overall design aspects of nanopositioners into the AC course. There were three important design questions that students explored with the new course materials: (i)

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how actuator choice (in the overall system design) can affect the performance of nanopositioners; (ii) how controller design can help improve the performance; and (iii) how novel designs can be used to overcome current limits on nanopositioners. In this context, the current course development is complementary to other efforts to introduce nanopositioning issues into AC courses, as described in previous works [21–23]. For example, a multidisciplinary course on nano-mechatronics with a focus on nanopositioning systems has been developed at the graduate level in [21]. At the undergraduate level, for existing AC courses, low-cost AFMs have been developed to illustrate nanopositioning control [22], and modules have been developed to introduce the dynamics and control of piezo-actuators used in nanopositioning [23].

Integrating new topics, such as nanotechnology, into existing courses (rather than developing new courses) can pose unique challenges due to the limited amount of lecture time available to deliver the new content. In general, the integration of new issues into the core undergraduate curriculum tends to increase the impact (since it affects more students in the program) when compared to the smaller number of students enrolling in specialized courses. Moreover, integrating new concepts into existing courses is advantageous when compared to developing new courses, since it is more difficult to add new (required) classes to typical engineering curricula, which are usually full. However, each required course tends to be typically full with required concepts; therefore, adding new material into an existing course is challenging also. Note that sufficient nanotechnology content needs to be added and integrated into the current course to enable learning new concepts. Our main approach to resolve this problem (of adding content without substantial increase in the time needed) was to integrate nanopositioner design issues with concepts already existing in the AC course (such as control design to increase bandwidth), and the use of homework (HW) to allow students to explore the application of course concepts into the nanotechnology area. While other mechanisms such as group presentations could offer an alternative to incorporate new concepts, the homework-based approach can be particularly useful if the available class time is limited. At UW, this AC course is an elective offered at the senior year after students have taken the pre-requisite course on system dynamics, which covers frequency response and is required course in the ME curriculum. This facilitates the homework to not only link nanotechnology material to AC course concepts but also to ME concepts from previous courses, such as the use of frequency responses to model and understand system behavior and limits. We grounded the homework-based approach on three fundamental understandings with regard to learning: (a) the best way for students to learn new information is to link it to existing knowledge [24]; (b) broad conceptual understanding comes from organizing important facts and data within an overarching knowledge structure (in this case, students linked nanotechnology material to their existing ME conceptual knowledge) [17, 24, 25]; and (c) applying new knowledge (in this case, with homework problems) helps to make that knowledge more retainable and transferrable [17, 24, 25]. Learning assessment results demonstrated that students were well able to meet the learning objectives (discussed later).

The article is organized as follows. In Section 2, a brief review of nanopositioner design issues is provided, followed by a description in Section 3 of how the new material is integrated into the AC course. Results and discussion of the course evaluation are in Section 4, and conclusions are in Section 5.

2. Nanopositioner control issues

A brief review of nanopositioner bandwidth and design issues in increasing the bandwidth is provided in this section.

2.1 Bandwidth

It is shown that vibrations limit the tracking bandwidth, i.e., the maximum achievable position-tracking frequency with sufficiently-low positioning error.

2.1.1 Need to maximize bandwidth

Higher bandwidth can increase the throughput of systems, which employ nanopositioners. The costs of such systems (which use nanopositioners) are typically measured in millions of dollars, e.g., in the semiconductor and opto-electronic industries. Therefore, throughput is a critical factor in the cost-of-ownership equation, and hence, increasing nanopositioner throughput will have a direct impact on cost-reduction in these industries. Similarly, nanopositioners are used in Scanning Probe Microscopes (SPMs), which are key enabling tools in the experimental investigation and manipulation of nano scale (and sub-nano scale) phenomena. However, during high-speed operation of SPMs, movement-induced vibration leads to damage of the sample and/or probe as well as unwanted modification of the surface properties being investigated. Therefore, SPM systems (without vibration compensation) are operated at low speeds. Increasing the bandwidth of nanopositioners (used for SPM probe and sample positioning) can increase the operating speed of SPM. In turn, high-speed SPM can advance the discovery and understanding of dynamic phenomena, and increase the throughput of emerging SPM-based nanofabrication techniques, e.g., [26]. Therefore, there is a need to increase the throughput of nanopositioners.

2.1.2 Vibrations limit bandwidth

Vibrations tend to limit the positioning bandwidth. To illustrate, let the transfer function of a piezoelectric bimorph positioner (used for experiments in the course) be given by

$$\frac{V_s(s)}{V(s)} = G_p(s), \tag{1}$$

where the input is the applied voltage V and the output is the sensor voltage V_s that measures the positioner's deflection. The experimental frequency response of the experimental system is shown in Fig. 1, which plots the magnitude $M_p(\omega)$ and angle phase $\varphi_p(\omega)$ of the transfer function G_p at different frequency ω where

$$G_p(j\omega) = M_p(\omega)e^{j\varphi_p(\omega)} \tag{2}$$

and $j = \sqrt{-1}$. Note that the magnitude $M_p(\omega)$ plot shows peaks corresponding to the resonance excitation of different vibrational modes of the system. Moreover, zeros of the transfer function $G_p(s)$ lead to a dip in the magnitude of the frequency response—such dips tend to appear between the vibrational-resonance frequencies. Ideally, for perfect tracking of generic position trajectories, with frequency content in the frequency interval $I^*_\omega = [0, \omega*]$, the magnitude of the frequency response should be constant over that interval I^*_ω. However, variations in the frequency response, due to, both the resonance peaks and the dips, can distort the positioning precision. Therefore, the tracking bandwidth ω_{bw} is defined as the frequency below which the frequency-response magnitude does not change significantly from the value at zero frequency (i.e., the DC gain). The amount of acceptable variation (e.g., 3db) of the frequency-response magnitude, from the DC gain, depends on the precision needed in positioning. The first vibrational resonance frequency ω_1 of the system results in a sharp peak in the frequency response (due to low internal damping) as seen in Fig. 1, which tends to limit the tracking bandwidth of the nanopositioner. Without vibration control approaches, positioning bandwidth with nanoscale precision is often limited to be less than 1/100th of the smallest resonant vibrational frequency ω_1 [9].

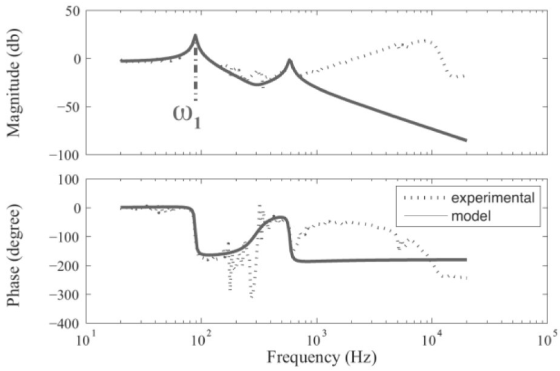

Fig. 1. Dotted line: Experimental frequency response (magnitude M_p and phase φ_p) of a piezoelectric bimorph actuator used in the AC course. Solid line: Fit of the low-frequency portion of the experimental response—such model fitting process is part of a pre-lab report for the AC course. Variations in the frequency response such as the peaks and dips in the magnitude M_p can distort the positioning precision [9, 10].

2.2 Range versus bandwidth

2.2.1 Need for large range

Large-range nanopositioning is important to bridge the gap between micro and nanofabrication, e.g., when linking compound geometric patterns containing nano-structures with their much larger input/output connections [27]. Similarly, large-range SPMs are needed for investigating nanoscale phenomena over relatively-large samples with dimensions in the hundreds of micron. The need for large-range nanopositioners has led to substantial research efforts in this area. For example, recent works have aimed to increase the nanopositioner range (without sacrificing precision) by using a flexural lever arm (see Fig. 2) to amplify the actuator's displacement [28, 29].

2.2.2 Range versus bandwidth tradeoff

Typical smart-material actuators (such as piezoelectric actuators) used in nanopositioners can achieve a range in the hundreds-of-microns, provided relatively-large actuators are used. The difficulty is that the mechanical, vibrational-resonance frequencies (e.g., ω_1), and therefore, the tracking bandwidth tend to be lower for larger smart-material actuators. The tradeoff between range and vibrational-resonance frequency is illustrated for an example piezoelectric actuator. While the expressions (for range and resonance-frequency) are different for other types of actuators, the dependence of range and resonance-frequency on the size of the actuator remains similar. The range R of a piezo-

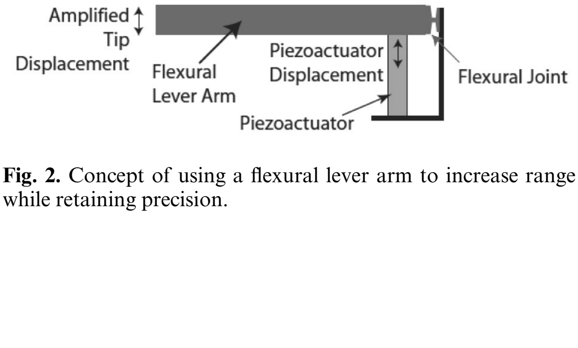

Fig. 2. Concept of using a flexural lever arm to increase range while retaining precision.

electric bimorph actuator is given by the following: (from the expression for bending-caused tip-displacement of a cantilever beam due to a moment M)

$$R = M\frac{L^2}{2EI} = \underbrace{\left\{\left(\overbrace{\left(d_{31}\frac{\bar{V}}{h}\right)EA}^{force}\right)h\right\}}_{moment}\frac{L^2}{2EI}$$

$$= \frac{3\ d_{31}\bar{V}}{h^2}L^2 \propto L^2 \tag{3}$$

where: the bimorph has thickness h, width b, length L, cross-sectional area $A = bh$, and area moment of inertia $I = bh^3/12$; the maximum possible voltage is $\bar{V}$ (set by material and depoling limits); d_{31} is a piezoelectric constant; and E is the Young's modulus.

The first vibrational-resonance frequency (ω_1), for an unloaded cantilever-type bimorph, is given by

$$\omega_1 = \frac{1.875^2}{L^2}\sqrt{\frac{EI}{\rho A}} = \frac{1.01}{L^2}\sqrt{\frac{Eh^2}{\rho}} \propto \frac{1}{L^2} \tag{4}$$

where ρ is the mass density. From the above two equations, the first vibrational-resonance frequency ω_1 is inversely proportional to the range R

$$\omega_1 = \frac{3.03\bar{V}d_{31}}{R}\sqrt{\frac{E}{ph^2}} \propto \frac{1}{R} \tag{5}$$

Therefore, large-range piezoelectric actuators tend to have lower vibrational-resonance frequencies, which result in lower tracking bandwidth. Thus, it is difficult to increase, simultaneously, both the range and the bandwidth of nanopositioners.

2.3 Automatic control (AC) to increase bandwidth

Essentially, automatic control (AC) approaches increase the positioning bandwidth by flattening the frequency response of the closed-loop nanopositioner in the region that contains the desired position trajectory's frequency content as illustrated in Fig. 3. There is substantial amount of work in this area—see [9] for a recent review.

2.3.1 Feedback to suppress vibration

Feedback control has been an essential part of nanopositioners used in early SPM development; for example, integral controllers are very effective in maintaining the desired probe-sample interaction, e.g., the desired level of tunneling current in Scanning Tunneling Microscopes (STMs) or the tip-sample force in Atomic Force Microscopes (AFMs). Integral controllers are particularly effective during low-speed operation; they can overcome both creep and hysteresis effects (in the actuators) and lead to precision positioning (since the vibrational effect is not dominant at low frequencies). In this sense, traditional proportional-integral-derivative (PID) feedback controllers or a double integral for tracking a ramp, are well suited for nanopositioning. Recent works have aimed to robustify such existing integral feedback controllers [30].

The main challenge in feedback design is to improve the positioning performance (without loss of system stability) in the presence of parameter uncertainty, non-minimum phase behavior and unmodeled, high-frequency dynamics with potential control spillover issues. Towards, addressing this challenge, starting with the early work in Ref. [31], modern feedback control techniques have enabled an increase in the bandwidth of nanopositioners. In particular, advanced control techniques are well suited to improve the precision and band-

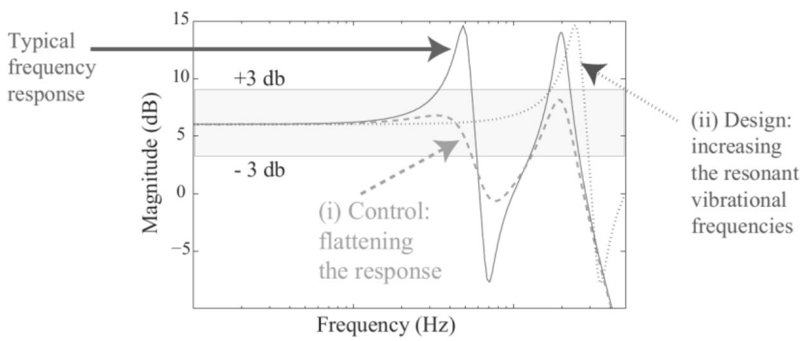

Fig. 3. Increasing of a nanopositioner bandwidth by: (i) control approaches to flatten the peaks and dips; and (ii) design approaches to increase the smallest resonant-vibrational frequency [9]. Solid line: response without control; dashed line: with feedback control; and dotted line: with design approaches. For this example, bandwidth is the frequency at which the frequency-response magnitude ($M_p(\omega)$ as in Eq. 2) does not change more than 3db from the value at zero frequency.

width of nanopositioners; see [9] and [32] for a review of such AC approaches.

2.3.2 Limit with AC methods

The bandwidth improvement with AC methods is limited to about the smallest resonant vibrational frequency ω_1. Without AC-based vibration-suppression approaches, nanoscale-positioning bandwidth is often limited to be less than 1/100th of the smallest resonant vibrational frequency ω_1. By flattening the response, positioning bandwidth can be increased to about ω_1. However, zeros in the system (typically between resonant vibrational frequencies, e.g., see Fig. 3) imply that the system does not have sufficient response, just after the first resonant vibrational frequency ω_1. Therefore, input saturation can limit the ability to drive the nanopositioner (with sufficient output response) beyond ω_1 for general trajectories. (*Although specific trajectories, such as sinusoids at the second resonant-vibrational frequency, could still be tracked.*)

2.4 Nanosteppers to increase bandwidth

One approach to avoid exciting the vibrations is to increase the smallest resonant-vibrational frequency as illustrated in Fig. 3. Smaller actuators tend to have higher resonant-vibrational frequencies, which tends to effectively increase the achievable bandwidth and therefore, to increase the overall throughput of systems using the positioner. However, as discussed earlier, smaller actuators tend to have smaller range. Another approach to increase the range is to use nanosteppers, which increase the positioning range by making multiple nano-steps as illustrated in Fig. 4.

The nanostepper's vibrational-resonance frequencies (and therefore the bandwidth) can be increased (by decreasing the size of the actuators) without sacrificing range. This is because a reduction in the size of the actuators in the nanostepper (to increase bandwidth) does not limit the number of steps that the nanostepper can take, and therefore does not limit the range. Smaller actuators imply that the nanostepper needs more steps to change the position by a specified value; however, the maximum positioning speed is not affected by using smaller actuators. To illustrate, let the maximum frequency of steps N_{max} be a fraction α of the actuator bandwidth, i.e., $N_{max} = a\omega_1$. Then, the maximum positioning speed V_{max} is independent of the actuator length (L) because V_{max} is the product of the range R and the stepping frequency N_{max}—from Eqs. (3,4)

$$v_{max} = a\omega_1 R = 3.03\alpha\ \bar{V} d_{31}\sqrt{\frac{E}{ph^2}} \qquad (6)$$

Thus, the maximum positioning speed V_{max} is not affected when the length L is reduced to increase the bandwidth—the approach overcomes the bandwidth-range tradeoff. AC is still beneficial to reduce vibrations induced when the nanostepper makes each step, and therefore to increase the positioning precision.

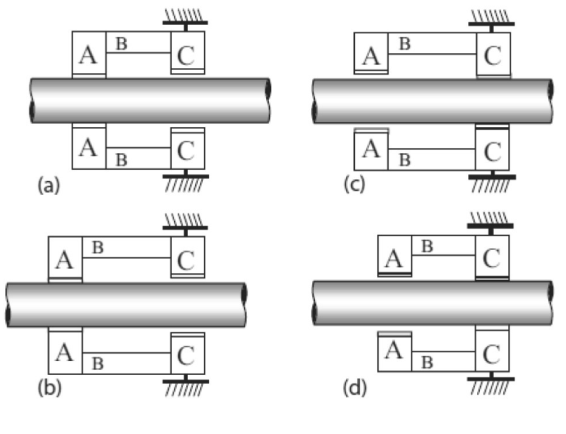

Fig. 4. One step of the nanostepper (also referred to as an inchworm) to move a rod to the left. (a) Actuator A clamps to the rod, (b) actuator B expand, (c) actuator C clamps and A releases, and (d) actuator B contracts. Nanosteppers typically use piezoelectric actuators.

3. Nanopositioning Module

3.1 Pedagogical issues

The goals, for the nanopositioning module, are to include the following analysis and design issues into the AC course.

(1) Nanosteppers analysis: modeling and control of piezo actuators used in nanopositioning systems.
(2) Design: devices to overcome bandwidth and range tradeoffs in nanopositioning systems

The specific learning objectives are shown in Table 1, which also shows connections between the learning objectives and the different cognitive processes that were targeted. By identifying the cognitive processes required to achieve the learning objectives (based on the work of Benjamin Bloom [33] and Anderson and Krathwohl [34]), we were better able to sequence the presented nanotechnology information and to develop homework problems that fostered the learning objectives. An additional aspect of learning is whether students were able to meta-cognitively understand how and what they were learning [34]. Metacognitive ability is often facilitated through introducing reflective exercises in which students examine and assess their own learning processes. However, we felt

Table 1. Rubric of learning objectives and evaluation methods. Additionally, students were asked to provide feedback on their experience with an end-of-course survey.

Learning Objectives	Remember, Understand	Apply, Analyze	Evaluate, Create
Definition of Bandwidth Student is able to clearly and fully define the term 'bandwidth'	HW 8 Bonus Part 1 HW 9 Prob 5.1		
Definition of Range Student is able to clearly and fully define the term 'range'	HW 8 Bonus Part 2 HW 9 Prob 5.2		
Find Bandwidth of Nanopositioner Student is able to correctly determine and record the bandwidth of a given Nanopositioner.		HW 8 Bonus Part 1 HW 9 Prob 5.1	
Find Range of Nanopositioner Student is able to correctly determine and record the range of a given Nanopositioner.		HW 8 Bonus Part 2 HW 9 Prob 5.2	
Find relation between Bandwidth and Range Student is able to correctly determine and record the relationship between bandwidth and range of a given Nanopositioner.		HW 8 Bonus Part 3	
Understand Bandwidth/Range Tradeoffs Student is able to fully and correctly describe the general principles of tradeoffs with regard to bandwidth and range.			HW 8 Bonus Part 4 HW 9 Prob 5.8
Control to Improve Range/Bandwidth Student is able to correctly design a controller to improve the range/bandwidth of a given Nanopositioner.		HW 9 Prob 5.3-5.7 Pre-laboratory HW 9 Bonus	
Novel Designs to Overcome Range/Bandwidth Limits Student is able to design a piezo-based positioning system that overcomes the tradeoff between range and bandwidth			HW 10 Bonus

that introducing reflective activities would overly complicate the course. Nevertheless, students were asked to provide some feedback on their experience with an end-of-course survey.

3.2 Module description

Due to limited amount of lecture time available to deliver the new content, the nanopositioner issues were mainly developed through brief in-class presentations, homework assignments that required further topic exploration, and an additional nanopositioner-based laboratory experiment. The nanopositioning module was integrated into the later part of the AC course after bode plots and standard bandwidth concepts were introduced as part of the traditional AC course, with examples such as motor position and speed control.

The initial foray into nanopositioners was through a bonus problem (with four parts) in the eighth homework (HW) set. (It is noted that one HW set was assigned in every week of the ten-week course and each HW set consisted of four to six problems). This was followed by required and bonus problems in HW 9, and a bonus problem in HW 10. Additionally, an experiment to design and implement a controller for a piezoactuator-based nanopositioner was included between HW 8 and HW 10; with a pre-laboratory assignment due before HW 9. The details of the assignments are discussed below.

Bonus (optional) HW problems were used because this was the first attempt at integrating nanotechnology in this course and we were cognizant of the possibility of content overload. Additionally, we were interested in seeing whether students were personally interested and motivated to learn the material, since motivation is closely tied to successful learning [17–20, 24, 25]. We anticipated that allowing for student choice with bonus problems might demonstrate their motivation and provide some impetus for self-study.

A challenge in using bonus HW problems is that not all students were expected to attempt them—this could lead to some students not having sufficient preparation for subsequent assignments. To avoid such a scenario, detailed solutions to the bonus problems (in HWs 8 and 9) were provided to the students' right after the HW was due and before they attempted the next HW. Moreover, a brief discussion (five to ten minutes) of the main issues in the HW problems was held during regular class meetings, typically, right after the HW was due.

3.2.1 HW 8 bonus problem

Let the strain ϵ produced in the piezoelectric bimorph actuator (piezo) be proportional to the electric field V/D where V is the applied voltage and D is the thickness across which the voltage is applied—this is one half of the total piezo thickness h.

- HW8 Bonus Part 1: Given the effective Young's Modulus E of the piezo, length L, and width b, find an expression for the displacement of the

piezo tip when it is cantilevered on one side. (Develop an expression based on your previous knowledge from your *Strength of Materials* course.) Write the expression for the positioning range R (maximum tip deflection when the applied voltage is the maximum possible $\bar{V}$).
- HW8 Bonus Part 2: Do some research to find the expression for the first resonance frequency ω_1 (first mode of vibration) of a cantilevered beam (piezo in this case), which represents the bandwidth of the piezo actuator. The variables in this expression should only be the dimensions of the piezo, its mass density ρ, and Youngs Modulus E.
- HW8 Bonus Part 3: Show that the first resonance frequency ω_1 is inversely proportional to the range R of the piezo actuator.
- HW8 Bonus Part 4: Discuss the consequence of this inverse relationship on positioning control.

3.2.2 *Experimental controller design*

3.2.2.1 *Experimental setup*

The experimental system consists of a piezoelectric bimorph actuator; the input is the applied voltage and the output is the tip displacement measured using a reflectance sensor. The experimental system's design is discussed in Ref. [35], which provides details of the experimental setup. Students implemented their controller using OpAmp circuits. They recorded both the open loop response and the closed loop response and comparatively evaluated the settling time for the two cases. The anticipated experimental improvements with the control system were compared to the theoretically predicted improvements (based on the model) as part of the pre-laboratory report. The impact of the controller design on bandwidth was studied as part of HW 9 bonus problem.

3.2.2.2 *Pre-laboratory report*

Model the system with 2 zeros and 4 poles up to 600Hz using the command *invfreqs.*

- Plot the Bode plot of the model and the data and compare.
- Design a proportional controller using your model. Choose the controller gain K_p using root locus (e.g., *rlocfind* command in MATLAB).
- Compare the step response of the open-loop system and the closed loop system.
- You will be given the error signal; design an OPAMP circuit to generate the input u to the piezo system. Analyze your circuit—note the input u must be $u = K_p e$, where e is the positioning error.
- Find the phase and gain margin of your controller, i.e., of $L(s) = C(s)G(s)$ using the fitted model as well as the original experimental data.

Comment on Pre-laboratory report: An example code for using MATLAB command *invfreqs* was provided to the students as a handout along with the measured experimental frequency response data. The resulting comparison of frequency responses (from experiment and from model) is shown in Fig. 1.

3.2.2.3 *Post-laboratory report*

Compare the responses found experimentally with your predicted response (for open and closed loop systems).

3.2.3 *HW 9 problem 5*

This problem deals with the use of control to improve bandwidth of nanopositioners without reducing the range. Consider the open-loop model of a piezo-bimorph system given by

$$\frac{Y(s)}{U(s)} = G(s) = \frac{K_{DC}\ \omega_1^2}{s^2 + 2\zeta\omega_1 s + \omega_1^2} \tag{7}$$

This model only considers the first mode of vibration and neglects creep and hysteresis effects in piezoactuators. The input U is the applied voltage V and the output Y is the displacement of the cantilevered tip and the damping ratio is $\zeta = 0.1$. The DC gain K_{DC} (displacement per unit voltage) and the first natural frequency ω_1 can be found from the solution to HW 8 Bonus problem. The maximum applied voltage should be 50V.

- HW9 5.1: Find the range (maximum displacement when the input voltage is 50V). This value divided by the maximum voltage should be the DC gain.
- HW9 5.2: Find the first resonance frequency of the system.
- HW9 5.3: Draw the bode plot of the system and find the bandwidth of the system, which is defined as the frequency where the magnitude drops by 3dB—try using MATLAB command bandwidth.
- HW9 5.4: For tracking, we do not want a change (increase or decrease) in the magnitude. Find the tracking-bandwidth (frequency where the magnitude of the system changes, increases or decreases, by more than 3db from the DC gain value) using the bode plot of the system.
- HW9 5.5: Design a PD controller to reduce the settling time ten times with the overshoot less than 5. Hint: try the PD controller (used for motor position control) in HW 7.
- HW9 5.6: Compare the step responses of the open and closed loop systems when the reference signal is $0.1R$ (one tenth of the range).
- HW9 5.7: What is the tracking-bandwidth of the closed-loop system? Compare it with the tracking

bandwidth and resonance frequency of the open-loop system.

- HW9 5.8: What conclusions can you infer from your results about the role of the controller in terms of improving tracking-bandwidth? For example, compare the control approach to increasing the tracking-bandwidth by reducing the range of the piezo by using a shorter piezo.

Comment on HW 9, problem 5. For properties of the piezo bimorph, students were provided with a handout of tables for different piezoelectric actuators from American Piezo Ceramics (APC) Inc., and asked to use data for a specific type of actuator (for the problem).

3.2.4 HW 9 bonus problem

Consider the model for the piezoactuator and the controller you designed for the laboratory (from the pre-lab). Compare the bandwidth of the open and closed loop systems. How does this relate to the results from problem 5 (in HW 9)?

3.2.5 HW 10 bonus problem

Can you come up with a design that can increase the range of a piezoactuator without reducing the bandwidth (i.e., without changing the size of the piezo)? Provide a sketch and explain how the system works. (Hint: do some online research on nano steppers.)

4. Results and Discussion

4.1 Design of the assessment

Design of the evaluation and assessment plan was based on the goals of this course development project and the learning objectives of the AC course. The goals of the project were to integrate nanopositioner design content with the standard content of an existing AC course without adversely affecting the amount of time students spent on the course, or their ability to achieve the course learning objectives. Additionally, the authors were interested in how well students achieved the nano-specific learning objectives (shown in Table 1), and the extent to which they were interested and motivated by the new nanopositioner design content. Homework grades and GPAs compared with prior courses were used to evaluate student learning. Student self-reported out-of-class workload was aggregated and compared with prior course results to determine effect on the time spent on the course. Student interest in, and motivation to learn the new material was assessed with an anonymous survey.

4.2 Assessment of HW

Designing learning assessments begins with a clear understanding of the learning objectives, and the expertise to determine what appropriate, observable evidence of learning should be. Table 1, shows each of the nano-related learning objectives, the cognitive processes required to achieve those learning objectives, and the specific course assignments that students used to produce evidence of their learning. Using homework assignments is standard practice in the ME program, and students are normally expected to devote two hours of outside class time on course assignments for every hour they spend in class. A grading scale (from 0 to 4) was used by the teaching assistant to score each of the homework assignments. The same teaching assistant graded each of the assignments in order to maintain consistency in the scoring. The scores for the students in the AC course (taught in fall 2010) are provided in Table 2 for the different HW problems in the module—the results are ranged from 0 to 4.

Table 2. Assignment scores (0 did not attempt; 1 poor; 2 some problems; 3 mostly good; 4 exceptional). Scores are from 29 of 31 students in course, who gave informed consent for use the data

	0 (%)	1 (%)	2 (%)	3 (%)	4 (%)	Average
HW 8 Bonus Part 1	65.5	13.8	20.7	0	0	0.55
HW 8 Bonus Part 2	72.4	7	3.4	0	17.2	0.83
HW 8 Bonus Part 3	82.8	0	0	0	17.2	0.69
HW 8 Bonus Part 4	79.3	0	0	0	20.7	0.83
Pre-laboratory Report	0	0	27.6	58.6	13.8	2.86
Post-laboratory Report	0	0	0	13.8	86.2	3.86
HW 9 Problem 5.1	0	0	0	48.3	51.7	3.52
HW 9 Problem 5.2	0	0	0	31	69	3.69
HW 9 Problem 5.3	0	0	3.4	41.4	55.2	3.52
HW 9 Problem 5.4	0	0	0	37.9	62.1	3.62
HW 9 Problem 5.5	3.4	0	0	41.4	55.2	3.45
HW 9 Problem 5.6	3.4	0	3.4	7	86.2	3.72
HW 9 Problem 5.7	3.4	3.4	31	17.2	44.8	2.97
HW 9 Problem 5.8	6.9	0	6.9	13.8	72.4	3.45
HW 9 Bonus	62.1	0	10.3	0	27.6	1.31
HW 10 Bonus	10.3	3.4	0	3.4	82.8	3.45
				Average Score for required problems 5.1–5.8 in HW 9		3.47/4.0

This was the first time this new course material was taught, therefore, the individual homework average scores shown in Table 2 could not be compared to results of similar assignments. However, the overall grade point average (GPA) of the required nanopositioner HW problems was compared to overall GPA for students in the course (Table 2). Additionally, the class GPA was compared to the GPA of the two most recent, prior iterations of the AC course taught by the same instructor (see Table 3), but without the nanotechnology content. The University of Washington's standard (anonymous) course evaluations ask students to self-report the average number of hours per week spent on course work outside of class. Table 3 also shows those averages.

4.3 Anonymous survey

The results of an anonymous survey completed by the students on the last class of the course is presented in Table 4—the results are ranged on a Likert scale from 1 to 5.

4.4 Discussion of results

Results demonstrated that the integration of nanotechnology into the existing automatic controls course was successful overall. As can be seen in Table 2 students achieved an overall GPA of 3.47/4.0 on the required nanotechnology HW problems (HW 9 Problems 5.1 to 5.8). This compared favorably with the course GPA of 3.48, which also falls within the GPA range achieved by students in the two prior iterations of the AC course taught by the same instructor, but without the nanotechnology problems. These averages are considered reasonable—typical average course GPA is in the 3.0–3.2 range for an undergraduate ME class at UW. Moreover, the overall workload with the inclusion of new nanopositioner design issues did not appear to be substantially different from previous versions of the AC course—the average number of hours per week spent on the course was 12.5 hours (mean value from 28 respondents) on the anonymous course evaluation. In the two previous versions of the course taught by the same instructor, without the nanopositioner design issues, students reported the average number of hours spent per week on the course as 11.3 hours (mean value from 25 respondents) and 14.8 hours (mean value from 29 respondents). This AC course was also successful with regard to increasing students' interest in nano related engineering (see Table 4, questions 1 and 2). Overall, students agreed that the nano device assignments were well designed and built well on their prior knowledge.

Results also indicate several areas where improvements could be made. As can be seen in Table 2, the bonus problem (in HW 8) was completed by less than a third of the students, and the few who did attempt the problems, performed poorly. This led us to conclude that, at the time, the nano content was still too new to the students. To ensure that all the students have the required background, we implemented a post HW discussion of the main issues that arose with the HW problems. We also assigned a controller design for an experi-

Table 3. Grade Point Averages (GPAs) and workload of three most recent AC course offering taught by the same instructor

Courses	GPA of required HW 9 problems 5.1-5.8	Course GPA	Average time spent on course work outside of class per week
Current AC course	3.47	3.48	12.5 (28 survey respondents)
Prior course A	N/A	3.0	11.3 (25 survey respondents)
Prior course B	N/A	3.6	14.8 (29 survey respondents)

Table 4. Student survey results (1 strongly disagree; 2 disagree; 3 neither agree or disagree; 4 agree; 5 strongly agree)

Survey question	1 (%)	2 (%)	3 (%)	4 (%)	5 (%)	Median
1. I was interested in learning about nano related engineering prior to this course.	0	13	43	30	13	3.4
2. Based on experiences in this course I am more interested in learning about nano related engineering.	0	9	22	57	13	3.8
3. The control-for-nanodevices assignments were well designed to help me achieve the course learning objectives.	0	9	18	64	9	3.9
4. The control-for-nanodevices assignments built well on the knowledge I gained in prerequisite courses.	0	10	29	43	19	3.8
5. For HW 9 you were asked to use prior knowledge to develop 'tradeoffs between bandwidth and range'. To what extend do you agree that you were prepared for HW9?	0	9	36	27	28	3.7
6. I am interested in a career in nanodevice engineering.	0	19	48	14	19	3.2

mental piezoactuator-based nanopositioner prior to HW 9. This gave the students an opportunity to work more closely with the nano content and related ME concepts. Students performed reasonably well on pre lab report for the experiment (2.86 average) and they did well on the subsequent required problems for HW 9. As a consequence, we may include a discussion section before HW 8, to motivate students to attempt the bonus problem in HW 8. Both the low scores and the low numbers of students who attempted the bonus problem on HW 9 indicated that there might be a minority of students who continued to struggle with the nanotechnology material at this stage (although there might be other reasons why they did not attempt the bonus problem). However, most students attempted and did well on HW 10 (bonus problem), which builds on previous concepts introduced in HWs 8 and 9, which might indicate that students were getting more familiar with nanopositioner design issues.

A concern with introducing new content into traditional courses such as AC is the need to tradeoff between new and old content due to constraints such as limited lecture time and the need to avoid student overload. Although the above use of homework to introduce new concepts in a class overcomes the limit on the available lecture time, such an approach could lead to student overload. In the AC course, several of the additional problems were offered as Bonus questions in HWs 8, 9, and 10, which offered choice for the students to attempt the problem or not. As discussed above, this bonus-problem along with classroom discussion did not appear to detract from the ability to understand nanopositioning design issues. Additionally, to reduce potential overload, the required HW 9 Problem 5 replaced a more standard problem on the same topic (Bode plots using standard second order transfer function) in the previous versions of the AC course. Additionally, a problem in HW 8 (in the previous version of the course) was removed since it was similar to other HW problems. Thus, an effort was made to ensure that the new homework problems did not lead to overloading. The overall workload (discussed earlier) with the inclusion of new nanopositioner design issues was not substantially different from previous version of the AC course. In general, if the workload is managed adequately, relying on homework assignments to engage students with emerging topics is a reasonable approach for integrating those topics into existing courses when available class time is limited.

5. Conclusion

We were interested in answering several questions regarding the integration of new nanotechnology content and learning activities into the ME course on automatic controls: (a) could new content be added without overloading the course or losing important content; (b) were the students able to achieve course learning objectives at an appropriately high level; and (c) were students interested in expanding their understanding of ME concepts in the area of nanotechnology and potentially pursuing nanodevice engineering? Results of our learning assessments and student feedback from a short survey show that, overall, students were able to meet course learning objectives in each targeted cognitive category, that the assignments were helpful to their learning, that the new nanotechnology content built well on their prior knowledge, that the students were not overloaded with the new material and assignments, and that a majority of students were interested in, or at least open-minded about careers in nanodevice engineering.

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