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Teaching System Modeling and Feedback Control Systems: A Multidisciplinary Course in Mechanical Engineering and Electrical Engineering

Prof. Li Tan, Purdue University, North Central

DR. LI TAN is currently with the College of Engineering and Technology at Purdue University North Central, Westville, Indiana. He received his Ph.D. degree in Electrical Engineering from the University of New Mexico in1992. Dr. Tan is an IEEE senior member. His principal technical areas include digital signal processing, adaptive signal processing, active noise and vibration control, data compression and digital communications. He has published a number of papers in these areas. He has authored and co-authored two textbooks: Digital Signal Processing: Fundamentals and Applications, Elsevier/Academic Press, Second Edition, 2013; and Analog Signal Processing and Filter Design, Linus Publications, 2009. He has served as associate editors for the International Journal of Engineering Research and Innovation, and the International Journal of Modern Engineering.

Dr. Jean Jiang, Purdue University, North Central

DR. JEAN JIANG is currently with the College of Engineering and Technology at Purdue University North Central in Westville, Indiana. Dr. Jiang has taught analog signal processing, digital signal processing, and control systems for a number of years. Dr. Jiang is a member of the Institute of Electronic and Electronic Engineers (IEEE). Her principal research areas are in digital signal processing, adaptive signal processing, and control systems. She has published a number of papers in these areas. She has co-authored two textbooks: "Digital Signal Processing: Fundamentals and Applications", Second Edition, Elsevier, 2012 and "Analog Signal Processing and Filter Design", Linus Publications, 2009.

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Abstract

This paper presents pedagogy and experiences in teaching system modeling and analysis as well as feedback control systems in the engineering curriculum. The course is a required multidisciplinary course to be offered at the junior level for both electrical and mechanical engineering students. In addition, electrical engineering (EE) students and mechanical engineering (ME) students who pursue an electrical engineering (EE) minor are required to concurrently complete a laboratory course. But regular ME students who do not pursue an EE minor are not required to take the laboratory course. The motivation for offering this multidisciplinary course is to increase learning efficiency for ME students pursuing the EE minor, since there is no need for them to take a dynamic system modeling course and a feedback control system course separately, and to efficiently use faculty resources. Furthermore, the course will enhance a collaboration between EE and ME students. This multidisciplinary course consists of two parts. The first part covers modeling and analysis of dynamic systems, including mechanical, electrical, thermal and electromechanical systems with an emphasis on mechanical system modeling, to meet the ME program requirement; and the second part deals with control system theory and applications consisting of both open loop and closed loop system analysis, and feedback control system design to meet the EE program requirement.

I. Introduction

The application and use of dynamic system modeling and analysis as well as feedback control system design are widely found in modern industrial machinery, automobile industry, sound and vibration control, and many areas of electrical and mechanical engineering[1-5]. This rapid advance has generated an increasing demand for engineering students with theory and skill sets in both dynamic system modeling and feedback control system design. In our engineering program, many mechanical engineering (ME) students pursue their undergraduate degrees with a minor in electrical engineering (EE) by taking four electrical engineering lecture courses and three laboratory courses. The feedback control system course and control system laboratory which are required in the EE curriculum are two of them. In the traditional EE feedback control system course, the topic of dynamic system modeling is lightly treated. On the other hand in the ME curriculum, students are required to take the dynamic system modeling course, in which control system theory is lightly covered. It can be seen that there some overlapping portions between the EE feedback control system course and the ME dynamic system modeling course. Hence, a multidisciplinary course is designed to combine these two EE and ME courses into one course. The motivation is to increase learning efficiency for ME students pursuing an EE minor, since there is no need for them to take a dynamic system modeling course and a feedback control system course separately, and to efficiently use faculty resources as well. The course will also enhance a collaboration between EE and ME students in general.

This paper describes a multidisciplinary course, which is offered at the junior level for both electrical and mechanical engineering programs. The course is created to meet the minimum requirements for both programs. It is different from the traditional ME dynamic system modeling course or EE feedback control system course[6-7]. The multidisciplinary course provides a foundation to ME students for the upper-level ME mechanical vibration analysis course[8-9] and it is also required to provide a solid background for EE students prior to take the upper-level EE digital control system course[10]. Besides the lecture course, EE students and ME students who pursue an EE minor are required to concurrently complete a laboratory course to obtain hands-on experience. This laboratory course is not required for regular ME students who do not pursue an EE minor. Hence, there are three groups of students: EE students, ME students minoring in EE, and regular ME students. To balance the content of the multidisciplinary course, the first part of the course covers modeling and analysis of dynamic systems, including mechanical, electrical, thermal and electromechanical systems with an emphasis on mechanical system modeling, to meet the requirement of our ME curriculum; and the second part deals with control system theory and applications to meet the requirement of our EE curriculum.

The designed multidisciplinary course uses the following strategies: theoretical development, software simulation assignments, and case study projects with real-world applications using MATLAB/Simulink. Furthermore, we carefully design the case study project for the feedback control system portion so that EE students and ME students minoring in EE are able to construct and test the project in their laboratory course using a LabView platform.

The paper is organized as follows. First, the course prerequisites, course content, and teaching methods will be explained. Second, the outcomes of students learning achievement will be addressed. More importantly, we will examine the course assessment based on the analysis of collected data from grading student course work, course evaluation and learning outcome survey. Finally, we will address the possible course improvement according to our assessment.

II. Course Outlines

The multidisciplinary course consists of the ME dynamic system modeling and EE feedback control system design (co-listed as ME 376/ECE 382) as shown in Figure 1 and is offered in the second semester in junior year with a 16-week class schedule. Three-hours of lectures each week are allocated. Concurrently, the control system laboratory course (ECE 308) is offered with three contact hours each week. The pre-requisite courses include Linear Circuit Analysis (ECE 201 and ECE 202), Electronic Measurement Techniques (ECE 208), Basic Mechanics (ME 270 and ME 274), and Engineering Analysis (ENGR 450). These prerequisite courses are also the common courses for both EE and ME students.

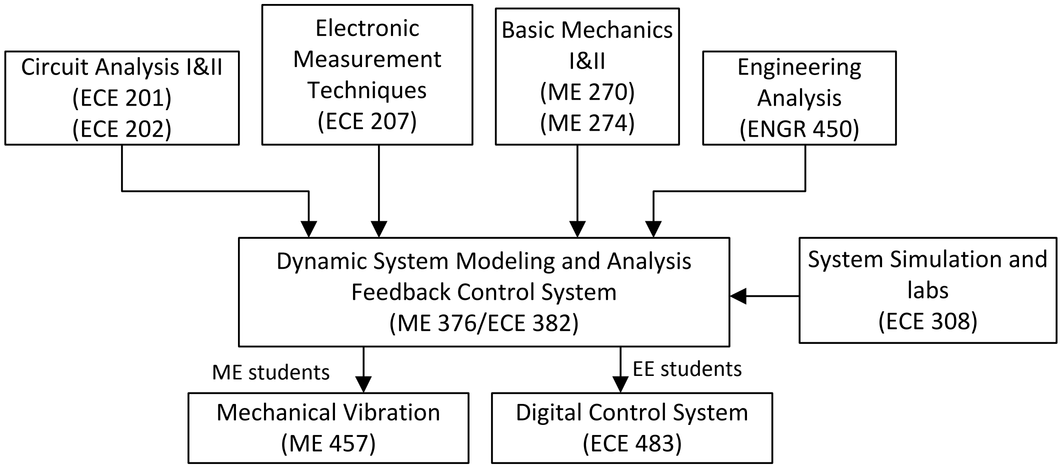


Figure 1 Flowchart of the related courses.

As shown in Figure 1, engineering students in Circuit Analysis I (ECE 201) gain the knowledge of circuit analysis in time-domain including AC analysis. Electronic Measurement Techniques (ECE 208) is the circuit laboratory course in which students acquire hands-on skills in using electronic measurement equipment. Circuit Analysis II (ECE 202) mainly deals with very important fundamental subjects[4-5]: Laplace transform, circuit analysis using Laplace transform, Fourier analysis, and filter design concepts. These topics taught in ECE 202 are extensively used in the dynamic system modeling and analysis/feedback control systems. Basic Mechanics II (ME 274) covers the mechanical dynamics which plays a key role for mechanical system modeling and analysis. Engineering Analysis[5] (ENGR 450) is the course for preparing engineering students with enhanced math skills and fundamental concepts for higher level engineering courses. The topics include differential equations, Laplace transform, matrix theory, vector calculus, orthogonal functions and Fourier series, boundary value problems, and partial differential equations. After successfully completing the multidisciplinary course, the EE students will continue to pursue elective courses such as Digital Control System[10] (ECE 483) while the ME students may take an elective course such as Mechanical Vibration Analysis[8-9] (ME 457) in their senior year.

Notice that this multidisciplinary course is designed to meet requirements for both ME and EE curricula. It is different from the traditional EE feedback control system course offered in many universities, since the portion of system modeling and analysis is required to be covered in depth by the ME program. The topics include modeling of rigid body mechanical systems, modeling of mechanical systems by an energy method, determining the mechanical spring constants for axial loading column elements via stress and strain analysis, spring constants for beam elements with a deflection analysis for various boundary conditions and spring constants for torsional elements, determining the damping constants for piston damper, shock absorber and torsional bearing damping, and modeling of gear systems, electrical circuits and electromechanical systems. The course balances the topic coverage to support both EE and ME electives, that is, the mechanical vibration and digital control system courses. Clearly, ME students who simply take the traditional EE feedback control system course do not obtain a sufficient preparation for the mechanical vibration course. Meanwhile, EE students who simply take the traditional ME dynamic system modeling course do not obtain a sufficient coverage for the feedback control system analysis and design, which will be required before taking the digital control system course.

A. Course Learning Outcomes

The multidisciplinary course covers the following major topics[6]: (1) dynamic system modeling (see additional topics required by the ME program listed in O1 in Table 1); (2) system of equations including state-variable models; (3) system solution using Laplace transform method; (4) system transfer function and stability analysis; (5) system simulation with MATLAB/Simulink; (6) steady-state error analysis for closed loop control systems; (7) control system parameters in the second-order system; (8) root-locus design method; and (9) various controller design and implementations. The course learning outcomes are developed and summarized in Table 1.

Table 1. Course learning outcomes.

O1. Model dynamic systems using differential equations. (additional topics required by the ME program: modeling of rigid body mechanical systems, modeling of mechanical systems using an energy method, determining mechanical spring constant for axial loading element, deflected beam element and torsional element, and determining damping constant for piston damper, shock absorber and torsional bearing damping)
O2. Describe dynamic systems using input-output equations, state variable models, and matrix format of state variable equations.
O3. Determine the dynamic system response using Laplace transform method for both differential equation model and state variable model.
O4. Determine the transfer function that describes a dynamic system, and analyze system stability and determine system impulse, step, and frequency responses.
O5. Use MATLAB/Simulink to conduct dynamic system simulations and interpret the obtained solutions.
O6. Simplify block diagrams of both open loop and closed loop control systems.
O7. Use Routh table to determine the stability of control systems.
O8. Given the block diagram of a type 0, 1 or 2 closed loop system and its transfer function, determine steady state errors for step, ramp, and parabolic inputs.
O9. Given a second-order system with a step input, determine the system characteristics such as damping ratio, damping constant, time constant, settling time, natural frequency, and damped frequency.
O10. Demonstrate how the root locus is constructed graphically and used the root locus to determine the transient response of a dynamic system.
O11. Given a specified damping ratio and settling time, design a P, I, or PI controller to control a first-order or a second-order process.
O12. Given a specified damping ratio and settling time, design a PD or PID controller to control a second-order process.

B. Case Study Projects and Laboratory

In order to fulfill our course learning objectives, two case study projects using MATLAB/Simulink are assigned to students. One deals with the system modeling, simulations and analysis, while the other aims for feedback control system design.

For the laboratory course taken by EE students and ME students for minoring in EE, a LabView platform is employed. Table 2 shows the layout of the case study projects in the multidisciplinary course and labs.

Table 2. List of case study projects and labs.

Multidisciplinary course (all EE and ME students)	Laboratory course (EE students and ME students minoring in EE)
	Lab 1 Op-amp amplifier and voltage follower, DC motor parameters
	Lab 2 Optical isolator and phototransistor for direction control of DC motor
	Lab 3 The Hall effect sensor for open loop control of the DC motor using LabView
Case study project 1: System modeling project (MATLAB/Simulink)	Lab 4 Damping ratio and natural frequency measurement of the SDOF system using LabView
	Lab 5 Temperature monitoring and open loop control using SCR switches with LabView
	Lab 6 Stepper motor control using LabView
	Lab 7 Armature controlled DC motor modeling and analysis using LabView
Case study project 2: Closed loop control system project (MATLAB/Simulink)	Lab 8 Closed loop DC motor speed control using P, I. PI controller of DC motor speed with LabView
	Lab project: PID control of DC motor speed using LabView

As shown in Table 2, case study project 1 overlays with Lab 4, in which EE students and ME students minoring in EE obtain experience on measuring and modeling damping ratio and natural frequency, and stiffness of a single-degree freedom system (SDOF). This lab will enhance the concepts of modeling system parameters in case study project 1 in the multidisciplinary course. Case study project 2 overlays Lab 8 and the lab project which are assigned for design and implementation of proportion (P), integration (I), proportion and integration (PI), proportion, integration, and differentiation (PID) controllers. All the modeling and simulations using MATLAB/Simulink are required in case study project 2 so that all the engineering students gain the design and simulation experiences of closed loop control systems.

Figure 2 describes an example of the first case study project, that is, vehicle system modeling and analysis using a bounce and pitch model. In this project, the student can pick any type of vehicle to work on. The student is required to find the vehicle parameters such as vehicle dimension, mass, mass moment of inertia, stiffness and damping constants. The road profile is assumed to be a sinusoidal function with a wavelength of λ. When a vehicle travels at velocity of v, the vertical displacements of the front and rear wheels are the time functions, which can be expressed as

$$z_2(t) = Z_{\max} \sin(2\pi v t / \lambda) u(t) \tag{1}$$

$$z_1(t) = Z_{\max} \sin[2\pi v (t - (l_1 + l_2)/v)/\lambda] u(t - (l_1 + l_2)/v) \tag{2}$$

where $z_2(t)$ is the vertical displacement of the front wheel while $z_1(t)$ the vertical displacement of the rear wheel. l_1 and l_2 denote the distances between the vehicle center of gravity and centers of front and rear wheels, respectively; and $u(t)$ is the unit step function. The system outputs are the vehicle bounce $x(t)$ and pitch $\theta(t)$.

Note that this two-degree freedom model is generic and can be applied to other similar dynamic systems. Furthermore, if a different road profile such as the road bumper is considered, equations (1) and (2) can be changed correspondingly for simulations.

The first case study project requires students to complete the following tasks: (1) develop system parameters, mathematical equations and state-variable model; (2) develop transfer functions and analyze system stability, frequency responses and behaviors; (3) obtain MATLAB/Simulink simulation results; (4) obtain analytical solutions using MATLAB script and interface the MTALAB program with the C program to enhance the computation speed; and (5) interpret the obtained results and find the maximum bounce and pitch scenarios.

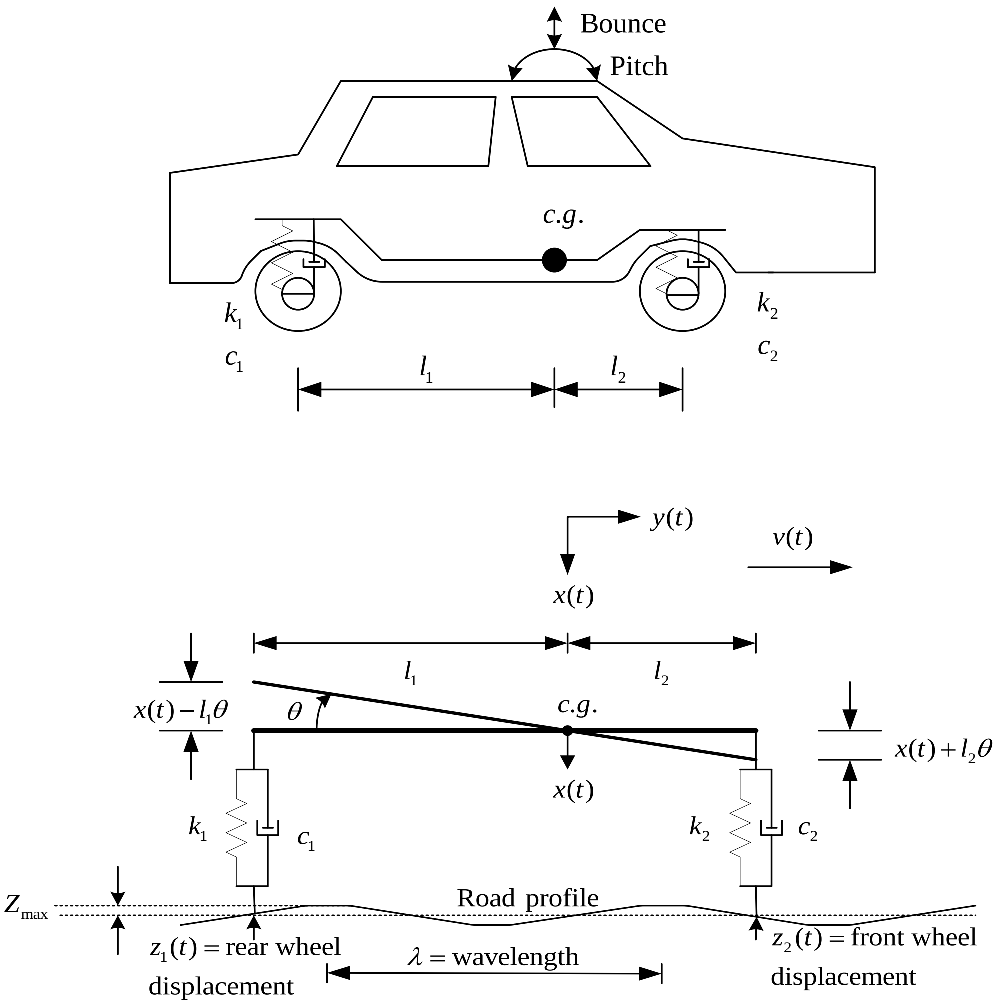


Figure 2. Dynamic system modeling, analysis and simulation using the bounce and pitch model.

As a simulation example, Figure 3 shows the developed MATLAB/Simulink program while Figure 4 displays the obtained bounce and pitch responses when the vehicle travels at 72 km/hour and the road profile is the sinusoidal function with the maximum vertical displacement of 0.05 meters and the wavelength of 10 meters.

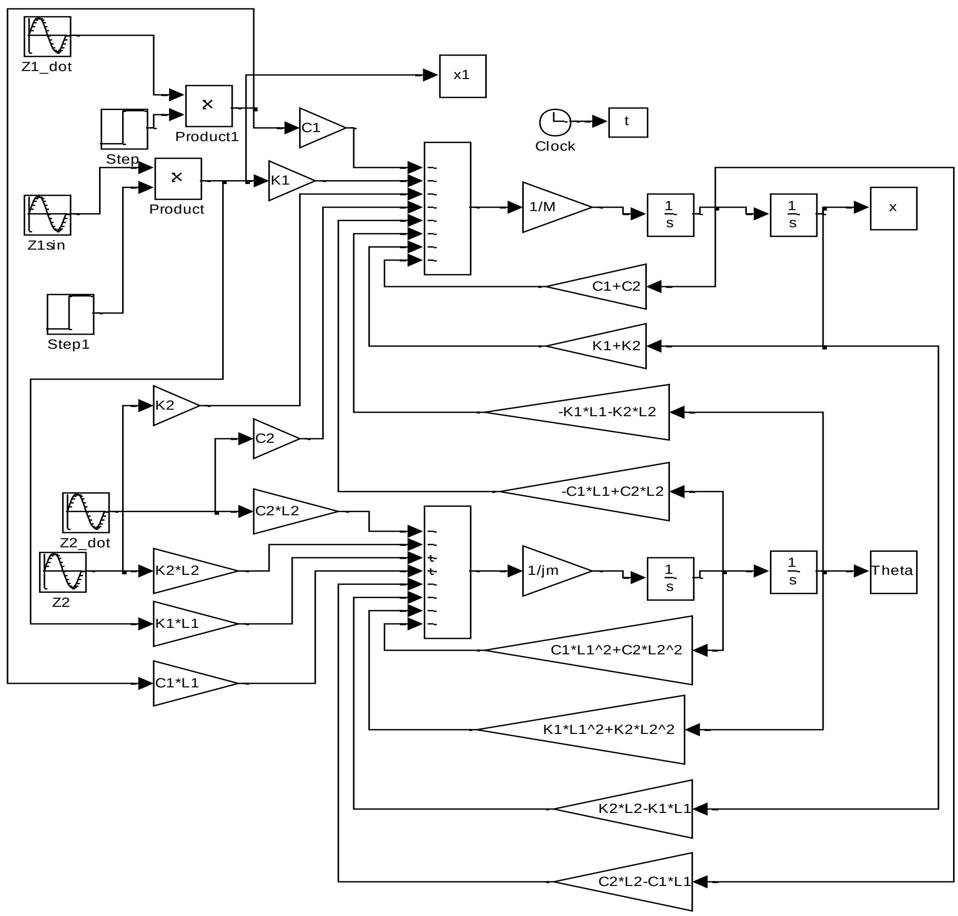


Figure 3. MATLAB/Simulink model for bounce and pitch simulations.

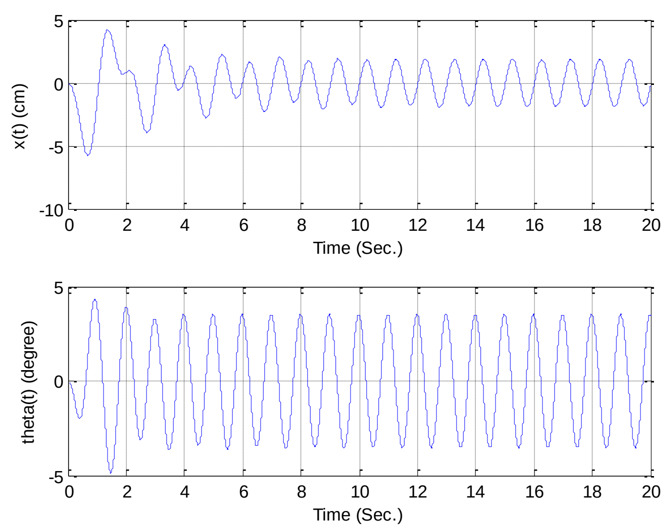


Figure 4. Responses of bounce and pitch of a vehicle traveling at 72 km/hour.

The second case study project consists of three parts listed below:

Part 1: Type 0 & Type 1 closed loop system analysis using MATLAB/Simulink.
Students use MATLAB/Simulink to simulate unity, negative feedback systems with a second-order process transfer function (armature controlled DC motor transfer function): $G_p(s)$ and controller transfer functions (P and I): $G_c = K$ and $G_c = K/s$, and measure the settling time, percent overshoot, steady state errors for the step and ramp responses, respectively.

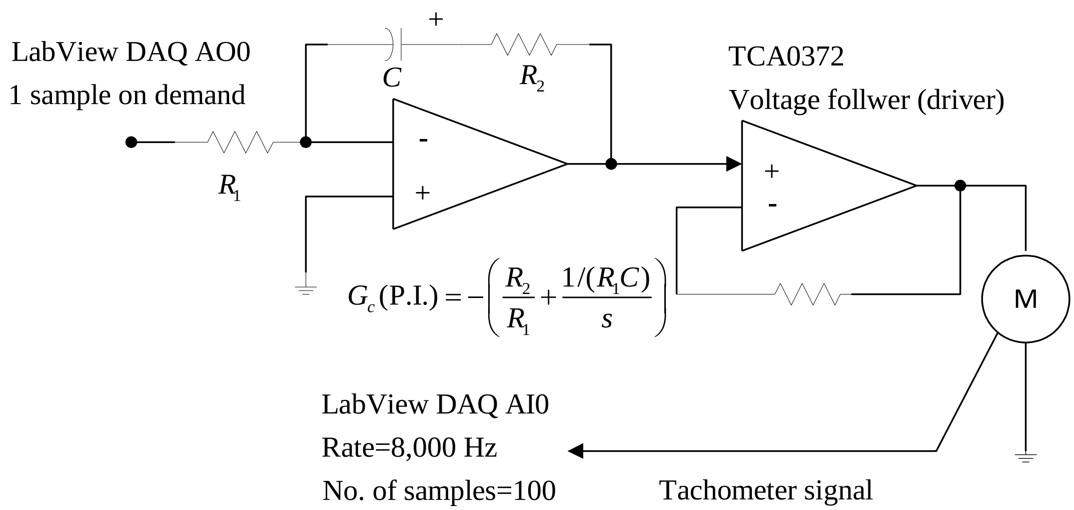
Part 2: MATLAB root locus and compensation design.
Students in this part learn how to use the root loci generated by MATLAB to design P, I, PI, and PID compensators; use MATLAB/Simulink to simulate the designed control systems and measure steady-state errors.

Part 3: DC motor modeling and control using P, I, PI, and PID controllers.
In this part, students use the modeling skill developed previously to model the given DC motor to obtain the equivalent transfer function, and then design P, I, PI, and PID controllers to meet the specifications of a closed loop control system and apply MATLAB/Simulink to simulate and test the designed controllers.

Besides completing these two case study projects and the course theoretical portion, EE students and ME students minoring in EE will complete the hands-on labs and a lab project.

C. Control System Laboratory

The laboratory course is divided into two parts. Labs 1-6 deal with sensors and actuators, data acquisition using LabView, system modeling, and open loop controls. They are designed for preparation for the feedback control system labs (labs 7-8) and a lab project, since the multidisciplinary course for the first half of the semester is dedicated to cover the dynamic system modeling and analysis. Beginning with the second half of the semester, the topics on the feedback control system will be covered. Students equipped with the labs skills continue to gain and apply knowledge of feedback control system theory in control system labs and project. For example, in Lab 8, students are required to design P, I, and PI controllers, respectively, to control DC motor speed. The hardware setup for a PI controller is depicted in Figure 5, where the DC motor to be controlled has a built-in tachometer, which generates the feedback signal (tachometer signal). The power operational amplifiers (TCA 0732) are used for implementation of the PI controller and the motor driver (Figure 5). The corresponding LabView software is shown in Figure 6. The speed command is inputted from the front panel (see Figure 6a) while the tachometer signal will be fed to an ADC channel via the LabView platform using a sampling rate of 8,000 Hz and a buffer size of 100 samples. The students are required to implement a zero-crossing algorithm to process the acquired tachometer signal (also displayed on the front panel) to produce the measured DC motor speed. The sum of the input command and the negative feedback is also implemented using LabView (see Figure 6b). The error signal, which is scaled via a numerical gain, is then sent out through the DAC channel to the designed PI controller. The control performance can be verified in the waveform charts displayed on the LabView front panel. Notice that the controller design and simulations using MATLAB/Simulink should be completed in case study project 2 in the multidisciplinary course.



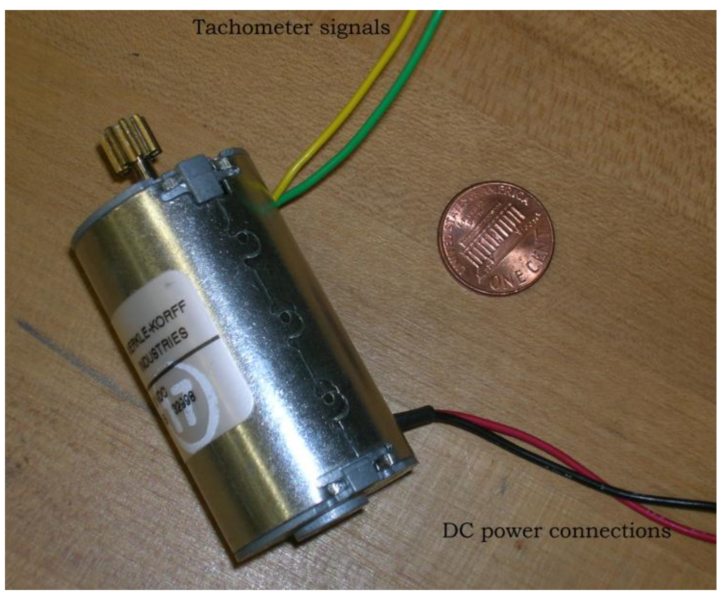
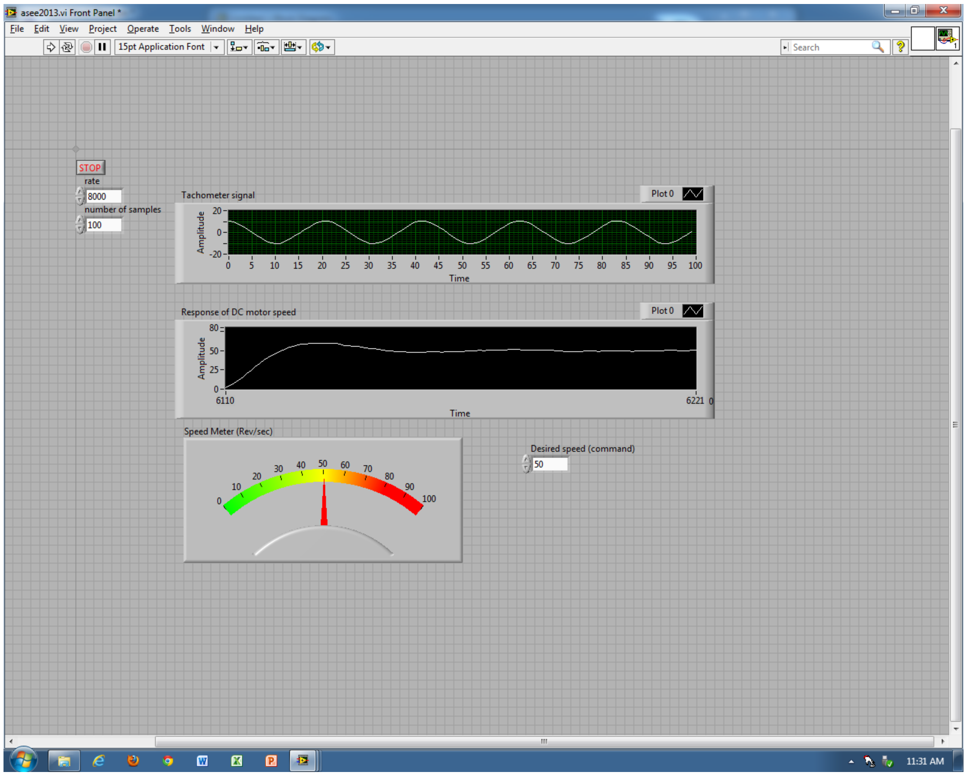
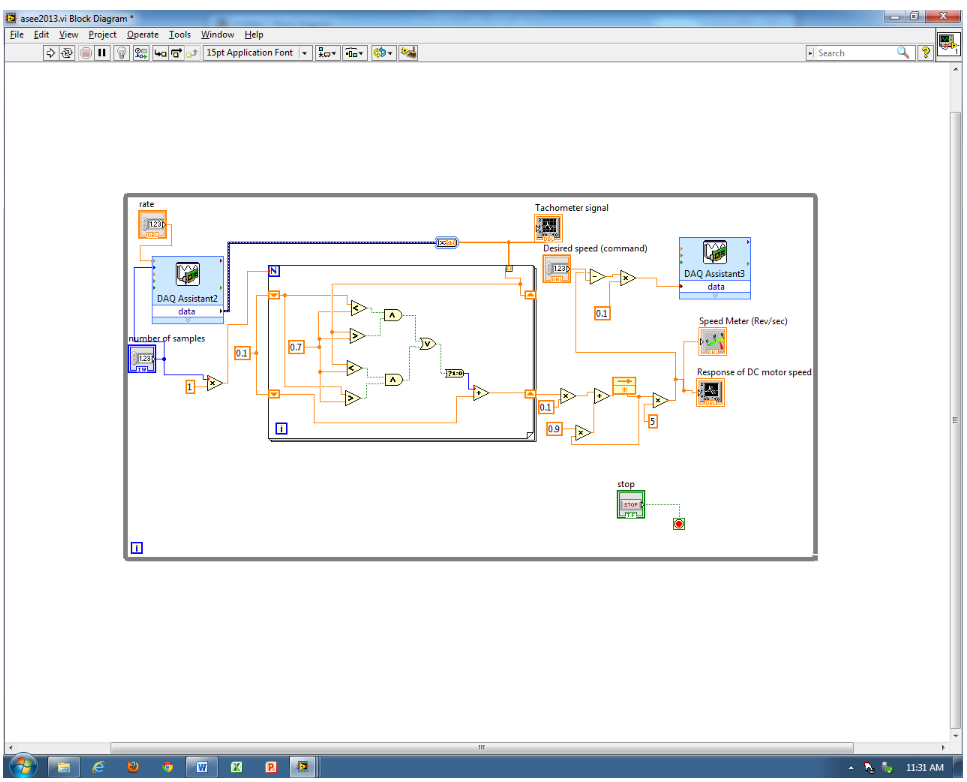


Figure 5. Hardware setup: PI controller, driver, and DC motor.



(a) Front panel



(b) Zero-crossing algorithm for speed detection

Figure 6. LabView Program.

III. Course Outcome Assessment

The assessment presented here with a total of 24 student responses (student distribution: 33% EE, 42% ME minoring in EE, and 25% regular ME) is based on our collected data from teaching the dynamic system modeling and analysis/feedback control system in spring 2011 and spring 2012. At the end of each semester, we conducted a student self-assessment. A student survey was given before the final exam to ask each student to evaluate his/her achievement for each course learning outcome listed in Table 1. Students were asked to make the following five (5) choices: understand well, understand, somewhat understand, somewhat confused, and confused. For statistical purposes, the five choices were assigned the scores of 5, 4, 3, 2, and 1, respectively. The average rating scores for all the course learning outcomes are listed on the second row in Table 3. To ensure the quality of instruction, we also conducted an assessment based on the final exams (direct measures). To do so, we designed a final exam in which course learning outcomes 1 to 12 (listed in Table 1) were fully covered by all the exam problems. We computed the average points from all the class members for the problem(s) corresponding to a specific course learning outcome. The instructor average rating score for a scale from 1 to 5 was obtained by dividing the average points by the designated points for that problem(s) and then multiplying the result by 5. The instructor average rating scores for assessing all the course learning outcomes are included in Table 3 concurrently.

Table 3. Student survey and instructor assessment.

Outcomes	O1	O2	O3	O4	O5	O6	O7	O8	O9	O10	O11	O12
Student Survey	4.75	4.67	4.67	4.75	4.42	4.50	4.75	4.25	4.17	4.0	3.75	3.67
Instructor Assessment	4.23	3.71	4.25	4.25	5.0	4.44	4.44	4.44	4.44	4.33	4.33	4.33

The average rating scores from both the student survey and the instructor assessment can serve as a reference to improve the course. For example, any course learning outcome achieving an average rating score below 3.5 will raise a concern and require an action plan for improvement. Figure 7 displays a comparison between the student survey and instructor assessment.

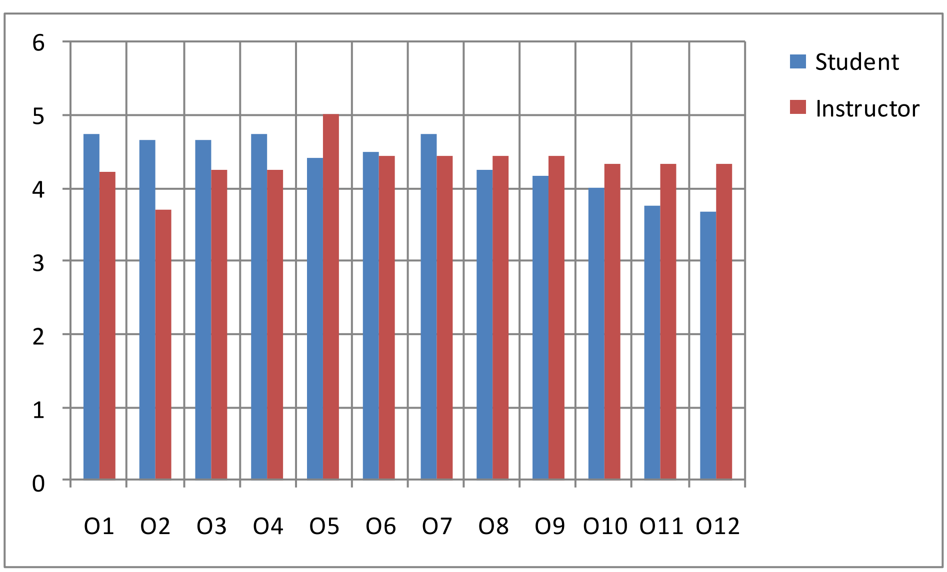


Figure 7. Comparisons of the student survey and instructor assessment.

From Table 3 and Figure 7, we can observe that

(1) The rating scores from the student survey and the ones from the instructor (direct measures) were consistent. The rating for course leaning outcome 2 (O2) had a bigger gap, in which the score from instructor rating was lower than the one from the student survey by 0.95. This discrepancy came from the fact that students understood the topics of system equation formulation, but made mistakes in their exams. The math proficiency is the area that requires improvement.

(2) Ratings for O8 to O12 are lower than the ones from the instructor. Students felt less confident than they actually perform in their exams. This indicates that more lecture time needs to be allocated for control systems. Overall, students had achieved their course learning objectives.

We also conducted another student survey regarding the case study projects and the use of software simulation tools. A set of questions were given to the students for evaluation and are listed in Table 4. Question 4 is only evaluated by the EE students and ME students minoring in EE. We used the following five (5) choices for students to evaluate the questions: strongly agree, agree, somewhat agree, disagree, and strongly disagree. The corresponding rating scores were assigned as 5, 4, 3, 2, and 1. The average rating scores are shown in Table 5.

Table 4. Survey questions for system simulation and control labs.

Q1. Do the case study projects significantly help me to understand the class material? Q2. Do the case study projects and presentation improve my self-learning ability and professionalism? Q3. Does MATLAB/Simulink tool used in the course efficiently assist concept development? Q4. Do LabView labs and project assist concept development (only for ECE308 students)?

Table 5. Student survey for system simulation projects and control labs.

Question No.	Q1	Q2	Q3	Q4
Student Survey	3.92	4.67	4.83	4.89

The average rating scores shown in Table 5 indicated what follows.

(1) Students strongly agreed that the case study project improved their problem solving ability.

(2) Most of the students liked MATLAB/Simulink and LabView used in the course.

(3) The rating score for Q1 (3.92) in Table 5 was relative low as compared to the others. This fact indicated that students had not only learnt concepts from the projects but also from class lectures, homework assignments, and MATLAB/Simulink simulations.

V. Course Improvement and Conclusions

We have successfully implemented a multidisciplinary course for EE students, ME students minoring in EE, and regular ME students. Based on our experiences in teaching the multidisciplinary course which essentially combines the control system course in the electrical engineering discipline with the dynamic system modeling from mechanical engineering discipline, we felt that the course contains well-established topics with a suitable pedagogy. Students have successfully achieved their learning objectives. Based on the course assessment, the lecture time allocation for covering control systems needs to be increased by appropriately reducing the lecture time for system modeling and analysis. The student math skills need to be improved in their pre-requisite courses. Finally, more practical and challenging case study projects can be assigned to students.

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