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Hands-on Experiments in Dynamic Systems and Control With High Student Throughput

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Abstract

Increased student enrollment with limited instructional resources poses significant challenges when attempting to meet the goal of hands-on experiences in system dynamics and control experiments in a mechanical engineering curriculum. A single-credit, co-requisite required laboratory course in system dynamics and control is redesigned to effectively quadruple throughput of student participation and credit-earning potential from prior course offerings. The strategy to accomplish this goal is described in this paper, as are examples of the experiments, activities related to the experiments, and the methods of assessment.

Introduction

The goal of a hands-on laboratory course in dynamic systems and control is to realize physical system experiments while maintaining meaningful experiential learning. Hands-on experiments are augmented with tightly coupled simulation exercises. A series of experiments in system identification augment a pre-requisite, junior-level dynamic systems modeling and analysis course (EML 4312), a pre-requisite to the laboratory course (EML 4301L) in the mechanical engineering curriculum. Experiments in control systems are used to augment a senior-level control of machinery course (EML 4313), a co-requisite course to the laboratory course as illustrated in Figure 1. Laboratory equipment is utilized by the one-credit, senior-level laboratory course (EML 4301L) in system dynamics and control that bridges the junior-level, three-credit course in dynamic systems to the senior-level, three-credit course in control systems.

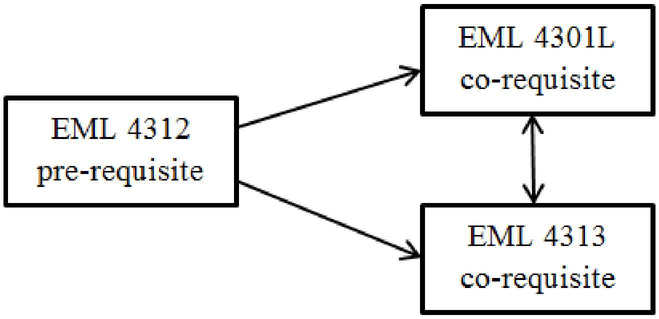

Figure 1: Course Relationship Diagram

The experiment resources used in the laboratory course consist of three different physical plant types. Replications of the physical plants contributes to the increased student throughput while also keeping the hands-on student teams to a minimum, three to four students per experiment during any given laboratory session. The students work in teams while performing the experiments, however, independent analysis and reporting is required and assessed. Examples of streamlined experiment activities are provided in comparison to experiments prior to the course revision. The streamlined experiments facilitate more efficient laboratory experiences while also increasing throughput of hands-on experiment activity, albeit in a trade-off with actual time spent with physical systems.

Correlated simulation of experiments in system dynamics and control are also discussed. Exercises in development of simulation models that correspond to the physical experiments are described. The strategy of scheduling the hands-on experiment activities in parallel with correlated system simulation to increase student throughput is also explained. The complementary simulation exercises enhance students' understanding of the experiments and also contribute to the throughput of the course. A grading rubric consisting of aspects of the hands-on experiments, simulation, and report writing is fully described. The assessment of this new approach to the laboratory course in system dynamics and control is included in the paper.

The goal of the course remains for the students to obtain first-hand experience with physical system modeling and control. A set of Educational Control Products (ECP) [1-5] laboratory physical system plants has been used in the course for several years to provide realistic hands-on experiential learning. The challenge is to maintain a reasonable level of hands-on learning with increased student enrollments. The ECP plants have also been used in hands-on experiments in dynamic systems and control experiments complemented with simulation [6-8]. Another approach is to create hands-on experiments that can be taken home [9]. Simulation alone is useful in process dynamics and control [10,11] and in aircraft dynamics and control [12]. Use of remote laboratories coupled with simulation is also another approach to involve real physical systems in experiments in dynamic systems and control [13-15].

Experimental System Plants

The ECP 210 Rectilinear Plant [1], shown in Figure 2 is configurable from a single Degree Of Freedom (DOF) to two DOF and three DOF by coupling the carriages with springs. In these various configurations, this system can be configured to a variety of plants including rigid bodies, flexibility in drives, and coupled discrete vibrating systems. It easily transforms into second, fourth, and sixth order plants to perform experiments with collocated or non-collocated control. A disturbance input motor allows additional flexibility to configure experiments in disturbance rejection for systems control. Multi-DOF configurations are easily assimilated for experiments in modal analysis and vibration.

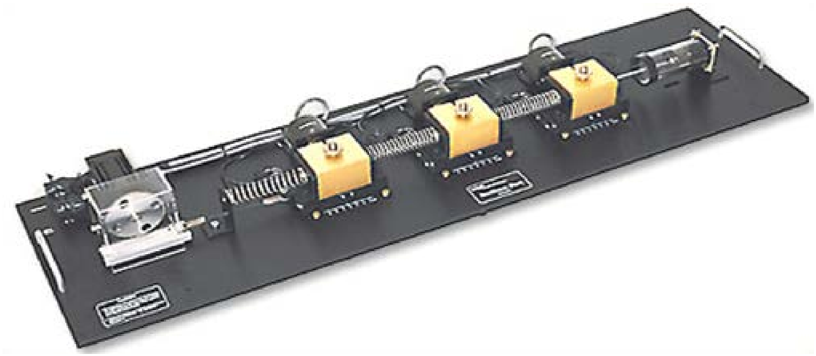

Figure 2: ECP 210 Rectilinear Plant [1]

Like the ECP 210 Rectilinear Plant, the ECP 205 Torsional Plant [2] shown in Figure 3 is configurable to one, two, or three DOF systems. Similarly, this system can be configured to a variety of plants including rigid bodies, flexibility in drives, and coupled discrete vibrating systems. It also easily transforms into second, fourth, and sixth order plants and likewise a disturbance input motor allow additional flexibility to configure experiments in systems control. Analogies between translational and rotational systems are readily exemplified in corresponding experiments in dynamics and control.

With the ability to be transformed into the variety of configurations the physical plants demonstrate both lumped parameter dynamics and generic control issues. The theory of motion of this type of mass-spring-damper system is very commonly treated in dynamics and controls courses. The physical plants create a control method evaluation and provide a practical laboratory basis for hands-on experiential learning.

Figure 3: ECP 205 Torsional Plant [2]

The ECP 220 Industrial and Servo Trainer Plant [3] shown in Figure 4 while featuring experiments in system identification and basic control, is also particularly useful for instruction of principles associated with control of machinery. A variety of transmissions can be configured utilizing timing belts, gear trains, and drive and load inertias. Additional practical control experiments in which non-ideal scenarios such as disturbance, friction, drive flexibility, and backlash are present can be studied and mitigated through experiments in feedback control. Further practical experiments address practical issues such as sensor quantization, sample period, and drive saturation provide a practical plant for applied control system fundamentals.

Figure 4: ECP 220 Industrial Emulator/Servo Trainer [3]

Additional physical systems are available for hands-on student learning in the Machine Science Laboratory. The ECP 750 Control Moment Gyroscope Plant [4], not shown, has four axes of independent motion for experimentation in multi-degree-of-freedom rigid body control, gyroscopic torque, advanced topics range from multi-input multi-output linear control to fully general nonlinear control with singularity avoidance. In addition, the plant may be used to emulate the control of satellite attitude. Thus, more sophisticated sets of experiments are also readily configured with this plant. The gyroscope has been used in a more advanced control course at the graduate level. The above plants may also be adapted to include the ECP A51 Pendulum Accessory [5] to allow for more configurations to create additional experiments in advanced control. The mechanism includes removable and adjustable moment-arm counter-weights on the vertical and horizontal rods for easy adjustment of plant dynamics. Thus, more sophisticated sets of experiments are also readily configured with this accessory added to one of the above plants. The pendulum has also been used in more advanced control courses at the graduate level.

Hands-on Experiments

A Machine Science Laboratory comprised of the systems described above supports fundamental theories in dynamics systems and control. ECP Systems [1-5] plants represent a series of physical hardware with dedicated software to perform demonstrations, experiments, and projects in system dynamics and control. The ECP laboratory equipment is utilized by the one-credit, senior-level laboratory course (EML 4301L) in system dynamics and control that bridges the junior-level, three-credit course in dynamic systems (EML 4312) to the senior-level, three-credit course in control systems (EML 4313). Thus, there are seven credits of course in system dynamics and control including laboratory. It has been found that the ECP 205 Torsional Plant, the ECP 210 Rectilinear Plant, and the ECP 220 Industrial Emulator offer the best match for the degree of complexity of experiments and hands-on learning to the theoretical topics covered in the two classroom courses. The laboratory equipment has been found to be robust and durable given being subjected to undergraduate students performing hands-on experiments of complex theories often for the first time. An overview of some of the experiments which have been used in the curriculum in various course offerings is provided in Table 1.

Table 1: ECP Systems Experiments [1-3]

	205	210	220
System Identification	X	X	X
Rigid Body PD and PID Control	X	X	X
Disturbance Rejection	X	X	
Collocated PD with 2 DOF Plant	X	X	
Non-collocated PD plus Notch Filter	X	X	
Successive Loop Closure with Pole Placement	X	X	
LQR Control	X	X	
Practical Control Implementation	X	X	X
Fundamentals of Servo Control			X
Control of Plant with Drive Flexibility			X
Control of Plant with Backlash			X

The ECP systems may be used in an undergraduate curriculum and a graduate curriculum. In the Machine Sciences Laboratory, two of the ECP 205 plants, two of the ECP 210 plants, three of the ECP 220 plants, two of the A51 Accessories and one of the ECP 750 plants exist. The gyroscope has been used in graduate courses of advanced control, however the use for system dynamics and control at the undergraduate level is found to be beyond the scope for use in the one-credit laboratory course. Likewise the pendulum has also been used in the graduate-level controls courses and is found to be less favorable at the undergraduate level, therefore experiments using these plants are not included in Table 1. Advanced control systems courses in which more advanced topics in experiments of the ECP 205 and ECP 210, experiments of the ECP 220, and experiments of the gyroscope and pendulum are used to gain hands-on learning of advanced control algorithms and methods.

While Table 1 provides an outline for the various types of hands-on experiments performed in the undergraduate laboratory course, the experiments can be further delineated into related, but separable activities. The ECP 205 Torsional and ECP 210 Rectilinear Plants [1,2] are configurable to the experiments in dynamic systems and control in the rotational and translational mechanical systems domains, respectively. For example: dynamic system identification of single and multi-DOF systems, one-DOF second-order damped oscillator, driven response of one-DOF second-order systems including step response, impulse response, linearity, convolution, harmonic response of second-order systems, two DOF systems (free Response, step response, harmonic response, frequency response), three DOF systems (free response, step response, harmonic response, frequency response), base mode excitation, rigid-body Proportional-Derivative (PD) and Proportional-Integral-Derivative (PID) control, disturbance rejection, non-collocated control, compensators and filters (lag, lead, notch), Linear Quadratic Regulator (LQR) Control, and additional practical considerations (saturation, discrete-time sampling, sensor quantization, sensitivity to parameters).

The ECP 220 Industrial Emulator and Servo Trainer Plant [3] while not all inclusive of the above, provides an additional set of topics for hands-on experiments is readily configurable to the experiments: system identification using transmissions, rigid-body PD and PID control, reflected inertia, transmissions, fundamentals of servo control, control with drive flexibility, control with backlash present, disturbance rejection, non- collocated control, compensators and filters (lag, lead, notch).

The one-credit laboratory course spans most of the experimental topics of the ECP 205, ECP 210, and ECP 220 and with the exception of the LQR experiments have been performed over time in the undergraduate curriculum. Keeping in mind that the one-credit laboratory course complements theoretical learning in two successive three-credit lecture course, the laboratory experience provides the benefit for the students to witness and realize theoretical concepts in action. Additionally, the students make use of MatLab and Simulink [16] in all courses in system dynamics and control.

The one-credit laboratory course was previously afforded three contact hours per week to enable in-depth experiments. Multiple sections of sixteen students per section allowed up to four teams of four students each ample time to perform in-depth, hands-on experiments as outlined in Table 1 and discussed above. Ideally, there would be four plants each so that all groups perform the same activity. The three-hour session has been favorable to perform a series of related topics and have the students perform the reconfiguring activities of the plants to obtain experimental data and complete an in-depth experiment. Table 2 summarizes the current resources that are utilized by the one-credit laboratory as well as the ideal for a section of sixteen students.

Table 2: Hands-on Laboratory Resources

	Current Resource	Ideal Resource
ECP 205 Torsional Plant	2	4
ECP 210 Rectilinear Plant	2	4
ECP 220 Industrial Emulator/Servo Trainer	3	4

With a resource equipment constraint and increasing enrollments, more sections have been added over time. Experiments have been rotated and performed in parallel to give students exposure to realization of theories applied to a variety of mechanical configurations. The adaptability of the experimental hardware lends itself to a high degree in variability of experimental topics, however, four groups of four performing the same in-depth experiment in a three-hour session is considered the optimum. The one-credit laboratory has been offered with this equipment in previous years with six to eight in-depth experiments run per semester by each student, rotating among classmates to a different group for a given experiment. Also, several instrumentation activities and experiments have complemented the course in this format using LabVIEW [17] in previous course offerings.

The Current Resource of Table 2 has been accumulated over time. As the plants have significant capital cost associated with them, moving to the Ideal Resource of Table 2 is part of the current five-year strategic plan of the mechanical engineering program. With full realization over time as a goal to complete the Ideal Resource, the hands-on learning component of the dynamic systems and control can occur and accommodate increasing enrollments.

Streamlined Experiments to Increase Student Throughput

With increased student enrollment, the time in terms of contact hours for the one-credit course has been reduced to half originally allocated from three hours to an hour and a half. Furthermore, the enrollment per section has been doubled from sixteen to thirty-two. This obviously presents challenges and requires trade-offs to maintain the hands-on experience. For a full-scale experiment, it typically takes approximately an hour for a student group to be fully up to speed, even with pre-laboratory assignments. With the current time allocation, insufficient time exists to conduct an in-depth, hands-on experiment as performed previously. By effectively quadrupling the student throughput, the hands-on experience and content is substantially reduced.

The new constraints require significant reconfiguration of the course. The experiments have been shortened and much of the set-up is done ahead of time for the student participants. Subsets of experiments are now performed in a streamlined format. Some data is now supplied with a given laboratory experiment, as opposed to having students collect all of their own data. Streamlined instructions for each of the laboratory exercises have being developed. Instrumentation activities and experiments using LabVIEW are no longer included.

Simulation exercises related to the hands-on experiments are assigned for each laboratory experiment. Simulations are performed using Simulink [16] in a separate Computer Laboratory independent of the experiments being performed in the Machine Science Laboratory where the ECP equipment exists. Half of the class performs hands-on experiments while the other half is assigned simulation performed in the Computer Laboratory in another location. The groups then rotate the following week so that all activities are performed by each group.

Typically four groups perform an experiment during a laboratory session depending on experiment resources available. This depends on the plant and the experiment being performed. In the past parallel experiments were run to keep the students engaged in hands-on experiments as discussed above. Experiments traditionally done in a contiguous session have now been reduced. In the initial streamlined offering of the course, the experiments are summarized in Table 3. Six streamlined experiments have been developed with corresponding simulation assignments.

Table 3: Streamlined Experiments

1	System Identification of Rectilinear Plant
2	System Identification of Torsional and Industrial Emulator Plants
3	Hardware Gains for Rectilinear, Torsional, and Industrial Emulator Plants
4	PD and PID Control for Rectilinear, Torsional, and Industrial Emulator Plants
5	Frequency Response for Rectilinear, Torsional, and Industrial Emulator Plants
6	PID Control for Industrial Emulator Plant with Effects of Transmission and Inertia

The first two experiments represent classic examples of topics that occur with second-order system dynamics and control. The corresponding schematics of the configuration for the ECP 210 Rectilinear Plant and ECP 205 Torsional Plant are shown in Figure 5.

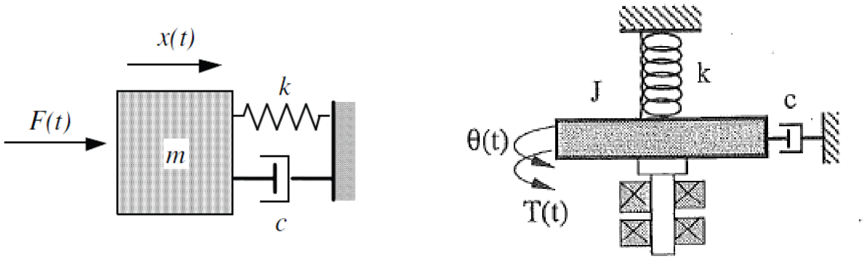

Figure 5: Single DOF Schematics for Translational and Rotational Systems [1,2]

A representative response plot for Streamlined Experiment 1 of Table 3 is shown in Figure 6. The students collect free response plots for this experiment and determine the system parameters of mass, stiffness, and damping through classical system identification procedures. Corresponding to each experiment, Simulink simulations are performed to validate the experiment. For example, the student would create a simulation corresponding to the free response of the Experiment 1 as shown in Figure 6 through the Simulink simulation shown in Figure 7.

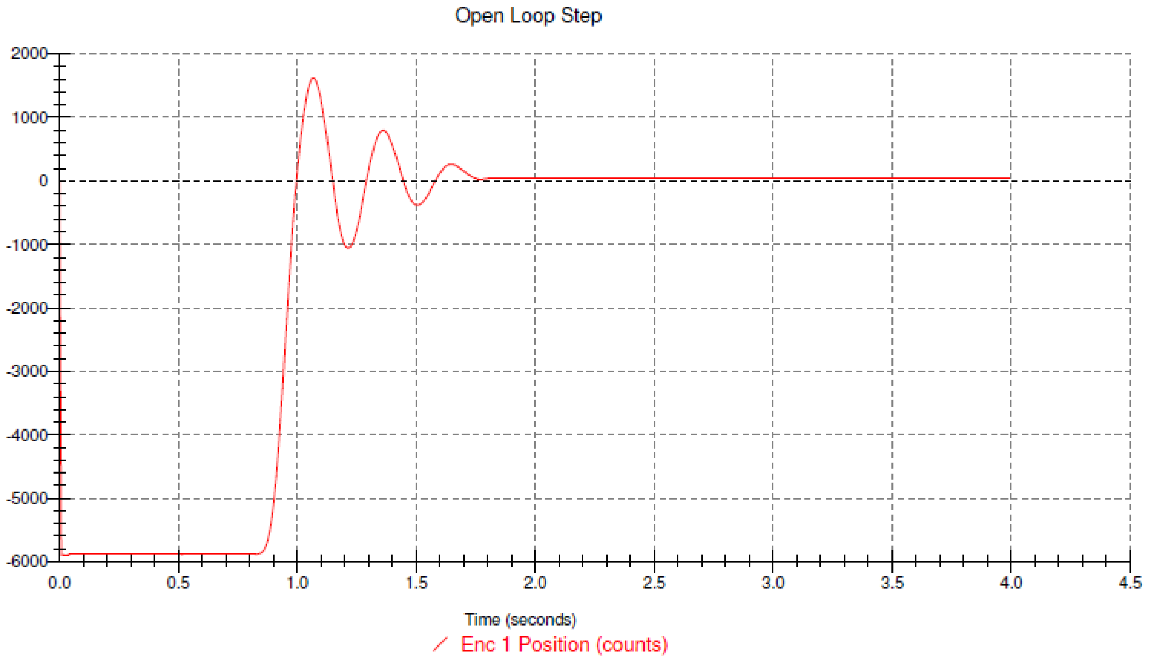

Figure 6: Free Response Output Plot of ECP 210 Rectilinear Plant

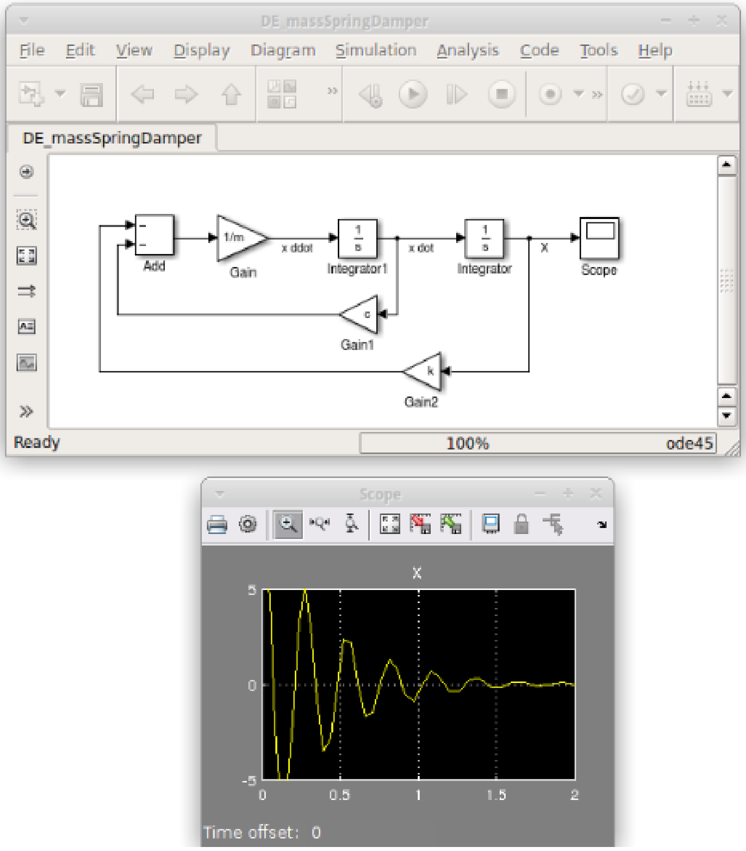

Figure 7: Free Response Simulink Simulation of ECP 210 Rectilinear Plant

Figure 8 shows a representative response plot from the Streamlined Experiment 4. The plants are configured ahead of time, and using the system identification parameters determined from previous experiments, this experiment involves creating desired responses via control settings for PD and PID controllers. Likewise is a subsequent experiment, a simulation of the second-order PID controlled response of Figure 9 corresponds to the actual plant response of Figure 8.

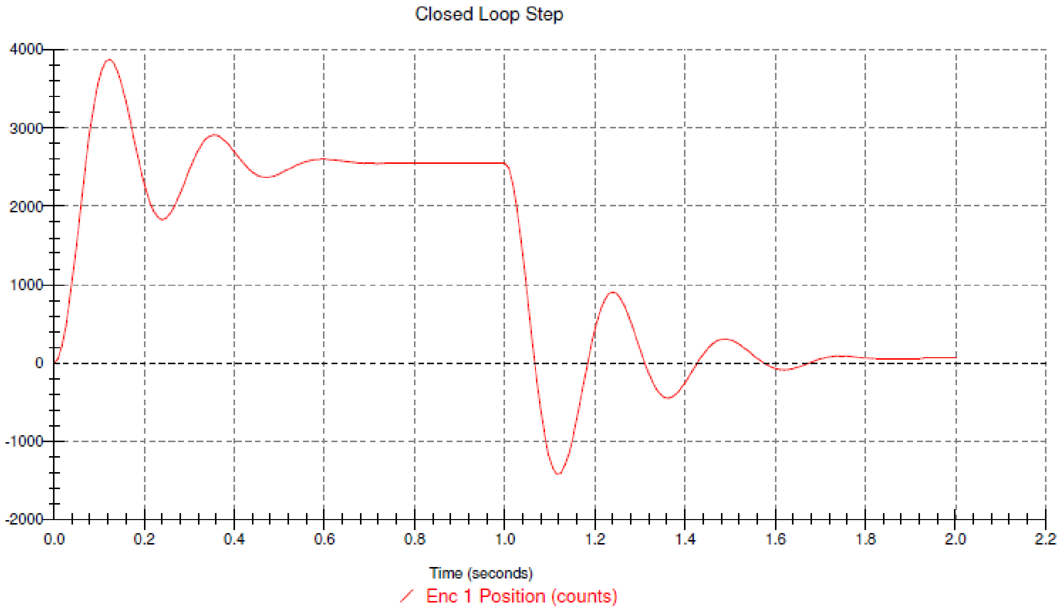

Figure 8: Step Response Output Plot of ECP 210 Rectilinear Plant

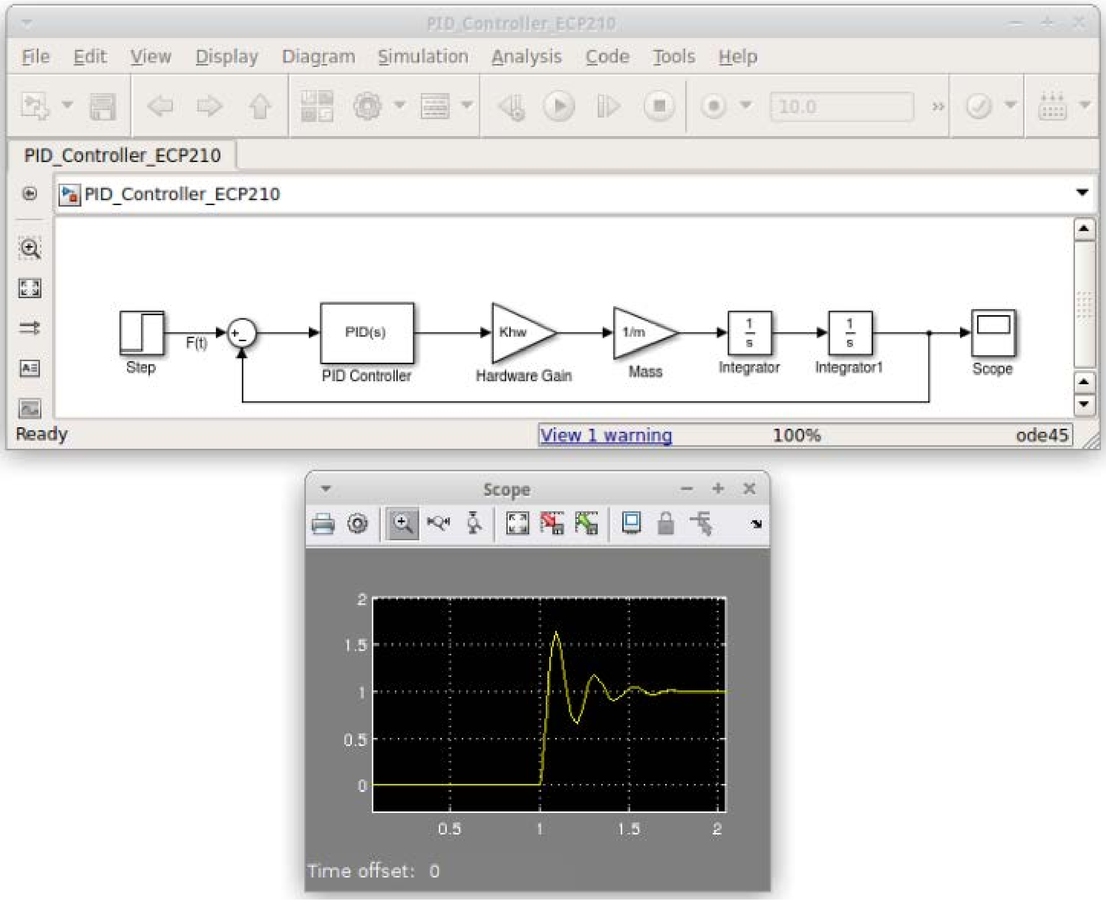

Figure 9: Step Response Simulink Simulation of ECP 210 Rectilinear Plant

In Streamlined Experiment 6 of Table 3, in addition to reinforcing design aspects of PD and PID controllers, the students obtain first-hand experience and observation of in the concept of reflected inertia in geared transmissions, a concept that is often difficult to visualize and theoretically grasp. In this set of experiments, two of the ECP 220 plants are configured with different transmissions. In Figures 10 and 11 respectively, a controller for one transmission configuration is designed and performed experimentally and simulated. In Figures 12 and 13 another controller and transmission with reduced reflected inertia is designed and performed experimentally and simulated encompassing effects on system response.

Figure 10: Step Response Output Plot of ECP 220 First Transmission

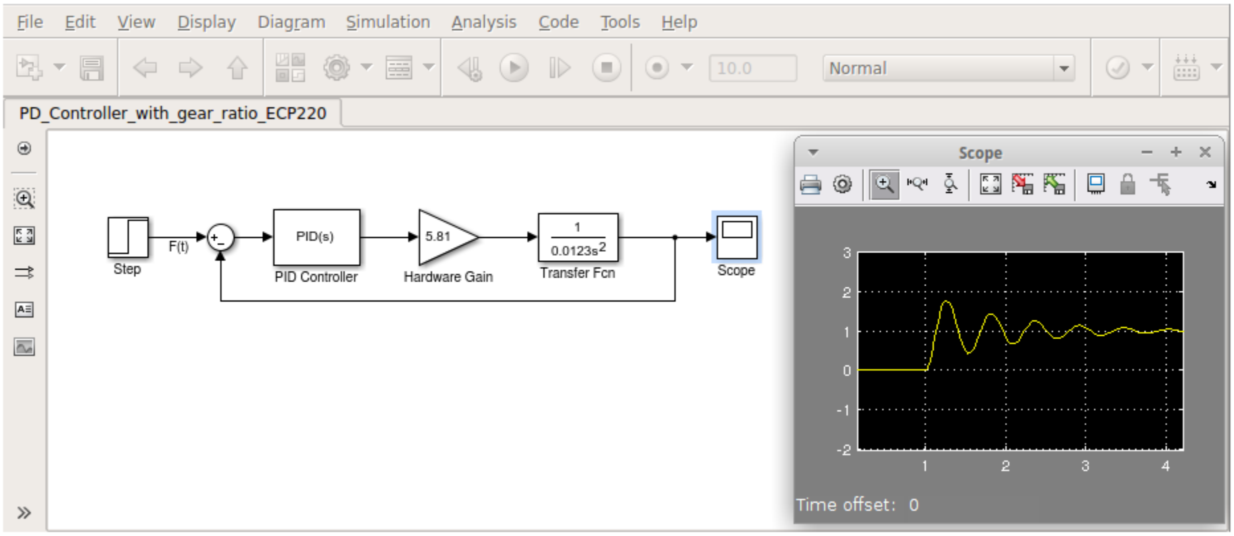

Figure 11: Step Response Simulink Simulation of ECP 220 First Transmission

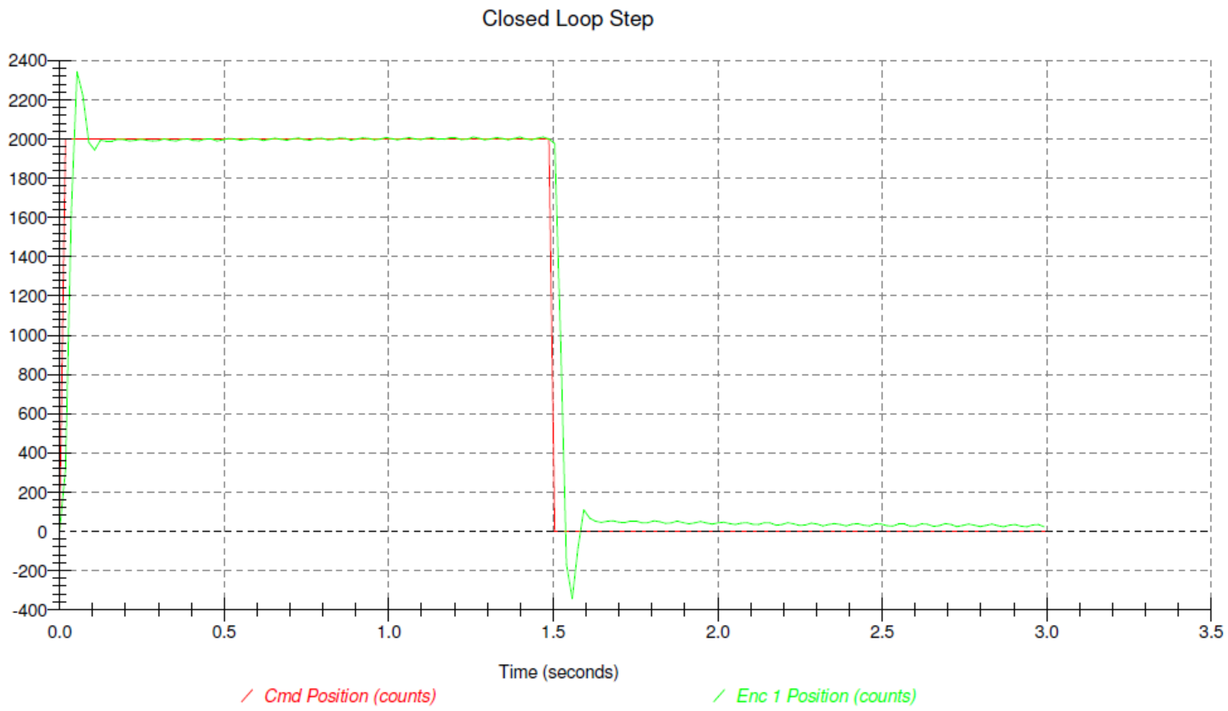

Figure 12: Step Response Output Plot of ECP 220 Second Transmission

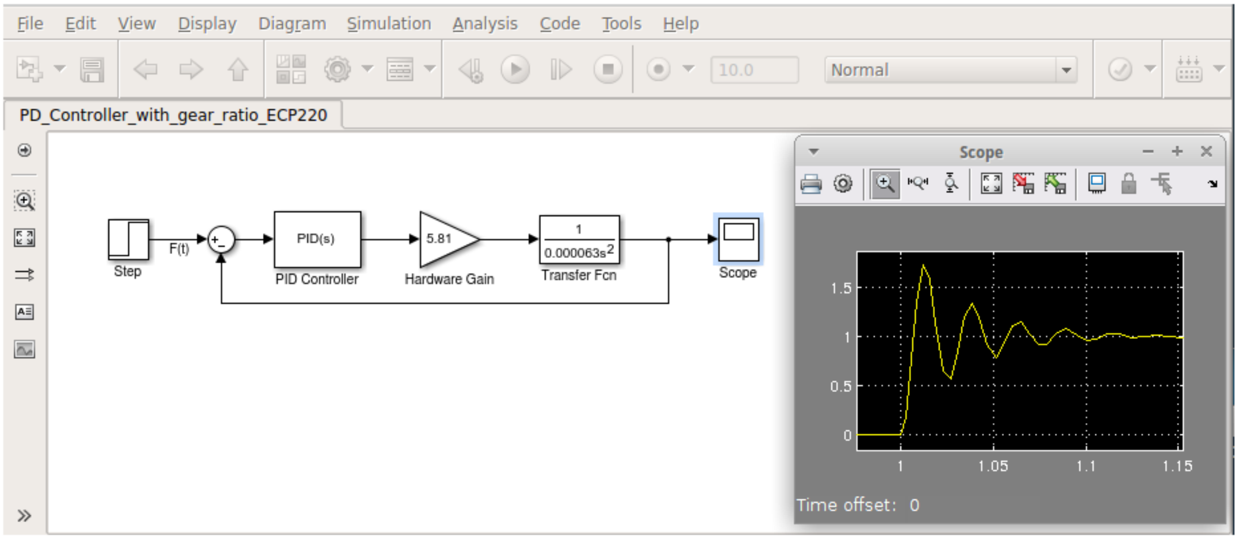

Figure 13: Step Response Simulink Simulation of ECP 220 Second Transmission

Assessment and Laboratory Reports

The student outcomes for the laboratory course are that at the end of the semester students should be able to:

1. Examine and analyze mechanical systems experiments as well as analyze and interpret data.
2. Build programs using modern engineering tools in instrumentation system software.
3. Conclude from basic principles of system identification and measurement, the parameters for mechanical system components.
4. Design and realize controllers for physical electro-mechanical system plants.
5. Compose engineering reporting of experiments and construct high quality technical reports following appropriate formats.

As the dynamics and controls courses have evolved over time, the hands-on experiments continue to be central to achieving all student outcomes listed above in the laboratory course. One aspect of streamlining the course is that less time is now spent on instrumentation system software, formerly supplemented with hands-on LabVIEW experiments. In the streamlined approach emphasis occurs now on supplementing hands-on experiments with simulation using Simulink. The primary assessment mechanisms are laboratory reports and an open laboratory report exam at the end of the semester. While the laboratory reports are a direct measure of Outcome 5, the end-of-semester exam also serves to help quantify Outcomes 1, 3, and 4. The actual performance of the experiments serves to accomplish Outcome 2. Although the exam questions may differ somewhat, they correlate to the student outcomes and the hands-on experiments as shown in Table 4. This can, at least anecdotally, help determine whether streamlining the experiments in order to increase the student throughput is detrimental or beneficial.

Table 4: Comparison of Exam Question Types

Question Type	Type 1	Type 2	Type 3	Type 4	Type 5
Experiment Type	1,2	3,4	5	3,4	3,4,6
Student Outcome	1,3	1,4	1,3	1,4	1,4
Av. Score Before Change	13/15	11/15	13/15	10/15	10/15
Av. Score After Change	13/15	13/15	13/15	14/15	10/15

As mentioned above, the questions are similar in concept but may differ in scope due to the streamlining of experiments, so improvements in results are not necessarily a one-to-one match as indicated by comparing the final two rows. Therefore a comparison is only anecdotal, not direct. The last row is selected test question scores after the course reconfiguration, while the row before is taken from the prior course offering before the reconfiguration. The apparent improvements are likely due to both increased use of simulation directly related to the experiments, coupled with reduction in complexity of experiments and subsequent exam questions due to streamlining of the experiments.

For each experiment shown in Table 3, each student creates an individual laboratory report. Although the students work in teams throughout the semester in performing experiments and corresponding simulations, each student is required to submit an individual laboratory report.

The reports are measured and quantified for qualities of results, and theory, formatting, data and use of data, simulation, and supporting attachments. A grading rubric for these metrics is shown in Table 5.

Table 5: Laboratory Report Grading Rubric (maximum score 50)

Score	0-3	4-6	7-10
Results and Theory	Little if any results for parameters are neatly tabulated in the main body and/or supporting theory is included in main body with detail in attachments if necessary.	Some results for parameters are reasonable and neatly tabulated in the main body and/or supporting theory is included in main body with detail in attachments if necessary.	Results for parameters are reasonable and neatly tabulated in the main body and supporting theory is included in main body with detail in attachments if necessary.
Formatting and References	Few report format guidelines are followed. The report is very limited in being concise with professional appearance and reference citations included.	Most report format guidelines are followed. The report is limited in being concise with professional appearance and reference citations included.	All report format guidelines are followed. The report is concise with professional appearance and reference citations included.
Data	Little use of data for results is summarized in the main body. Raw or summary data is omitted.	Some use of data for results is summarized in the main body. Raw or summary data is in attachments if necessary.	Use of data for results is summarized in the main body. Raw data is summarized/condensed in attachments if necessary.
Simulation	Little if any of recommended simulation included in the main body and/or supporting documentation of the simulation is in the attachments.	Recommended simulation is partially complete and discussed in the main body and/or partial supporting documentation of the simulation is in the attachments.	Recommended simulation is complete and discussed in the main body. Complete supporting documentation of the simulation is in the attachments.
Attachments	Little if any necessary attachments beyond the report page limit are included.	Some necessary attachments beyond the report page limit are neatly organized, have professional appearance, and referenced in the main body in the order they are referred to.	Any necessary attachments beyond the report page limit are neatly organized, have professional appearance, and referenced in the main body in the order they are referred to.

Conciseness and clarity are considered in assessment of the report. The tendency, as in the past is for the reporting to improve throughout the semester. For example, in the initial laboratory reports, the average score on the reports was 66%, while scores steadily improved whereas in the final laboratory report the average improved to 90%. These trends are similar to prior course offerings; however, the expanded grading rubric improves feedback to the student. The laboratory reports currently account for 75% of the course grade. Additionally, the end-of-semester exam discussed previously currently accounts for 25% of the course grade.

Concluding Remarks

A senior-level, one-credit laboratory course in dynamic systems and control is coupled to a junior-level, three-credit course in dynamic systems, and a three-credit, senior-level course in controls in a mechanical engineering curriculum. Laboratory equipment is utilized by the one-credit, senior-level laboratory course (EML 4301L) in system dynamics and control that bridges the junior-level, three-credit course in dynamic systems (EML 4312) to the senior-level, three-credit course in control systems (EML 4313). The goal of the course remains for the students to get first-hand experience with physical system modeling and control. The span of experiments of the ECP systems was presented to illustrate the breadth and depth of experiments possible, many of which have been performed in prior undergraduate- and graduate-level course offerings. Examples of a streamlined subset of experiments to accommodate the increased student throughput have been presented.

Limited contact time in the class has reduced the experiment content significantly in that the students experience less depth, hands-on inquiry, and discovery; however an adequate level of hands-on experience is maintained. By doubling the class size for each section of the laboratory, while simultaneously reducing the contact time in half, the student throughput is effectively quadrupled. There is no longer time in the lab session to review theories of the experiments so pre- and co-requisite courses are relied upon with further dependency than in previous course offerings.

A simulation for each experiment is done in alternating sessions for each experiment. The student teams also alternate so that equity in performing simulation pre- and post-experiment simulation is maintained. Ideally both would occur, however the throughput constraints pose this additional constraint. The simulation exercises are performed unsupervised in the Computer Laboratory in a separate location, while the hands-on experiments are performed under supervision in a laboratory setting in the Machine Science Laboratory.

Assessment occurs through observation of student teams performing experiments, laboratory reports, and an end-of-semester, open laboratory report exam. An expanded grading rubric for laboratory reports has improved feedback to the student. Comparison of similar types of conceptual questions of exams before and after course reconfiguration indicates that student learning outcomes are at least maintained with increased student throughput via streamlined hands-on experiments. In continuously improving the course under the new format, an increased emphasis on pre-lab exercises will be used to prepare the student for a more effective and enhanced laboratory experience. More in-depth experiments performed previously are streamlined so that in a trade-off, students obtain some level of realistic experience in physical dynamic systems modeling and control.

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