Collaborative Experimentation and Simulation: A Pathway to Improving Student Conceptualization of the Essentials of System Dynamics and Control Theory

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Abstract

The overarching goal of this research is to improve conceptualization of System Dynamics and Controls concepts by incorporating a Web-facilitated curriculum to enable inter-campus collaboration and remotely-accessible or virtual systems. This approach will complement lecture-based curricula and will strongly enhance students' conceptualization and exposure to System Dynamics and Controls fundamentals by providing less restricted exposure to a variety of systems that encompass the more important Dynamic Systems concepts.

The plan involves the development of a System Dynamics Concepts Inventory and the implementation and assessment of three Web-enabled laboratory formats: (1) inter-campus collaborative experimentation, (2) remotely-accessible experiments, and (3) virtual system experiments. Each format has its inherent advantages and disadvantages. Remotely-accessible experiments, for example, can be made more readily available to students outside of regular laboratory hours, but the lack of hands-on exposure limits the potential scope of the experiments. Each format has been preliminarily implemented using a variety of dynamics systems that reflect some of the more important fundamentals pertinent to System Dynamics. These activities are currently being incorporated into a laboratory course at the University of Texas at San Antonio (UTSA) and a lecture course at the University of Texas - Pan American (UTPA).

A preliminary Course Inventory is being developed in collaboration with faculty at both institutions. An initial assessment of each laboratory format has been completed. This paper reports on the findings including a detailed discussion of the development of the Course Inventory, a discussion of the pros and cons of implementing each format, and an evaluation of the impact of each format in addressing student conceptualization of a few key fundamentals.

Introduction

Engineering students struggle to understand the roles of dynamic systems modeling and control in engineering. They struggle to visualize the motion and dynamic response of physical systems.[1] Students often perceive dynamic systems concepts, especially automatic controls, as a "large collection of abstract math."[2] They get lost in the mathematics and struggle with conceptualizing implementation of fundamentals to predict and control the dynamic response of physical systems. Textbooks and chalkboards are not sufficient means for demonstrating the

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response of a dynamic system.[3] Effective tools are necessary to "demystify" the application of abstract mathematical concepts through visualization of realistic examples.[4]

Laboratories are essential to engineering education and have provided hands-on experience for students to physically implement engineering concepts. They are employed to develop, as opposed to simply reinforce, system dynamics concepts.[5] However, equipping a laboratory that is readily accessible to students is a major expense. The traditional laboratory format tends to require too much time, students receive disproportionate exposure to instrumentation due to the need to share equipment, teaching assistants must be properly trained to ensure effective instruction, and many universities simply cannot afford to maintain modern instrumentation readily accessible to students.[6] More readily utilized, economical laboratory solutions that address the above issues are needed to improve conceptualization of the fundamentals of dynamic systems and their control.

To address these issues, three inter-university laboratory formats utilizing virtual systems and remotely-accessible experiments are being developed to complement the Mechanical Engineering curricula at UTPA and UTSA. The laboratory formats provide inexpensive alternatives that are more readily accessible and available to students. *Virtual laboratories* provide students access to simulated experiments or animated dynamic system simulations. *Remotely accessible* laboratories allow students to access via the Internet real-time experiments with video feedback. *Inter-university laboratories* engage students in a collaborative effort to consolidate resources for a single project.

The goal is to effectively engage students in the engineering process of modeling and controlling dynamic systems. By implementing and assessing these laboratory formats, we intend to help students achieve the following objectives:

1. *Enhance conceptualization and use of fundamentals through multiple means of visualization.* The laboratory formats proposed will incorporate real-time animations, dynamic response plots, experimental video feedback, and physical data acquisition allowing students to interact with dynamic systems in a manner impossible using solely textbooks and figures.
2. *Increase participation through improved dissemination, accessibility, and availability of experiments via the Internet to students at many institutions.* By using relatively inexpensive media tools and the Internet, the experiments are more readily available to a large audience.
3. *Engage students collaboratively to improve understanding of system dynamics.* In industry and research, groups of engineers collaborate to combine resources. This cooperation is often facilitated by the Internet. Using a laboratory format proposed below, students at both institutions will collaborate to exchange simulation and experimental results.

As with any innovation in pedagogy, instruments are necessary to assess the effectiveness of new tools in addressing goals and objectives. Thus, a System Dynamics and Control Concept Inventory is being developed as part of this project. The current inventory, as discussed later, is an abbreviated version focusing on the concepts that pertain to the systems currently being implemented – a torsional plant, a rectilinear plant, an inverted pendulum plant, and a ball and beam plant. Along with the inventory, an assessment instrument partially modeled on the Foundation Coalition's Dynamics Concepts Inventory is being developed and has been initially tested.[7]

Laboratory Formats

Three laboratory formats are being implemented and tested. They incorporate multiple means of visualization and include individual and collaborative exercises. They are being applied to a variety of classical dynamic problems including a torsional vibration plant, a rectilinear vibration plant, an inverted pendulum, and a ball-and-beam system. These systems were chosen because of their availability at the participating institutions. Multiple formats will be applied to each application for comparison and critical evaluation of each laboratory format.

Inter-University Laboratory Format

Students at the two campuses will work in teams, as they would in a joint venture involving two companies or research groups in industry, to encourage collaborative learning (refer to Figure 1). Students at campus A will develop a computer-based model of the system using MATLAB/SIMULINK, which will simulate experimental test conditions and parameters. Students at campus B will perform the actual experiments, acquire data, and perform any necessary post-processing of the data using equipment available at campus B. This process will likely occur in an iterative fashion, where experimental conditions and parameters change with each iteration. This format is designed to consolidate resources that are not equally available at both campuses. Students at campus A will focus on understanding the use of modeling and simulation to predict dynamic response and to design controllers. Campus B students will focus on understanding the use of model validation by using experimental results. They will get hands-on experience in instrumenting a dynamic system for data acquisition and control. Roles of campuses A and B can be reversed for a subsequent project.

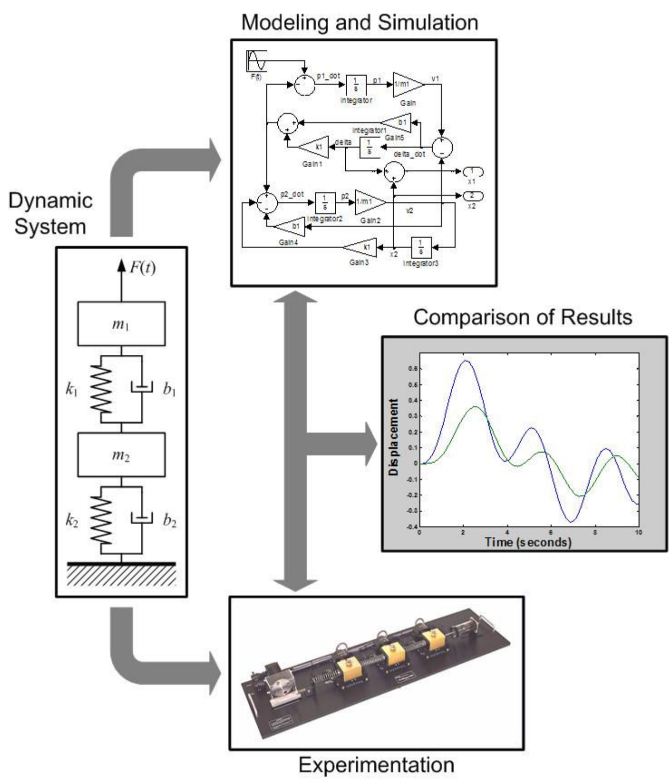

Figure 1: Collaborative experimentation format.

Remotely-Accessible Laboratory Format

As depicted in Figure 2, students will work individually to model a system that is remotely-accessible via the Internet as implemented and described in the references [7, 9, 10]. Mathematical representations will be simulated using MATLAB/SIMULINK. Experiments will be remotely accessed through a Web-page utilizing LabVIEW's *Remote Panels* for simple remote execution of LabVIEW on a server connected to the experiment through a data acquisition board. The Remote Panel allows students to manipulate parameters, collect data, and see the real-time dynamic response through a video feedback without the necessity for any specialized software on their local computer.[11] Additionally, this activity will be coupled to a 3D animation of a more complex "real-world" problem that will be developed using MSC VisualNastran 4D and will also be accessible via the Internet. This problem will build on the concepts from the laboratory system and is intended to help students expand use of concepts to real-world engineering problems. The MSC VisualNastran 4D model will allow students to change physical system parameters and to prototype controllers.

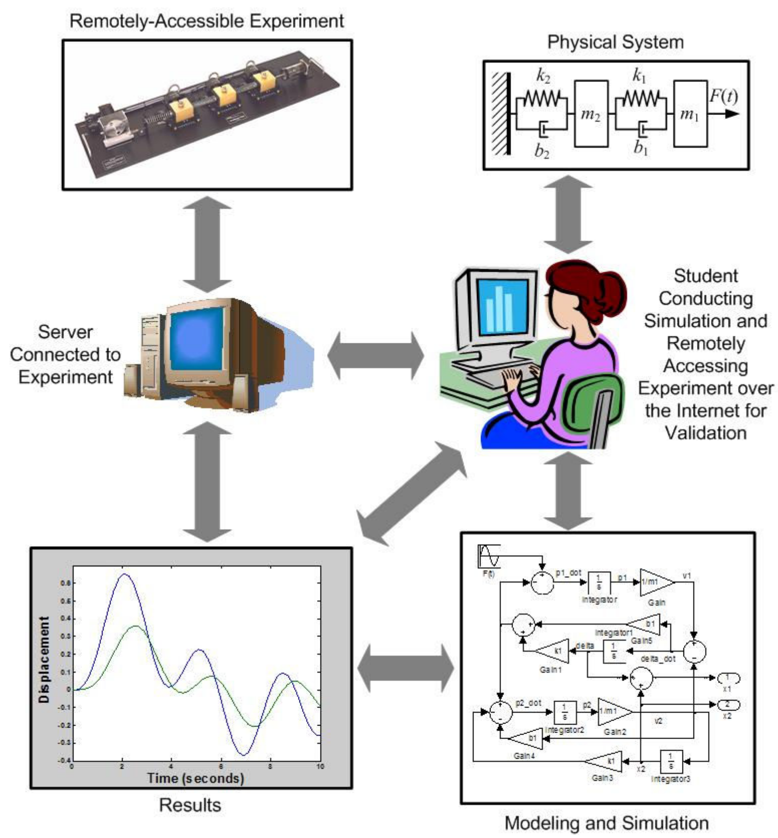

Figure 2: Remotely-accessible system format.

Virtual Laboratory Format

This format is similar to the previous format except that in place of a remotely-accessible experiment, a 3D virtual system (as defined in the references [12, 13]) that is developed using MSC VisualNastran 4D will be available for access via the Internet as described in the references [14, 15]. As depicted in Figure 3, the virtual system will provide as output animation and time- and/or frequency-domain plots. A

Java applet will be developed to allow remote access of the virtual system on a server from a web browser for simulation, data acquisition, and controller prototyping. The remote user will not need any specialized software. As in the previous format, students will develop models and simulations of the virtual system in MATLAB/SIMULINK. They will be able to upload their controller design to the virtual system, test its performance, and visualize the resulting response.

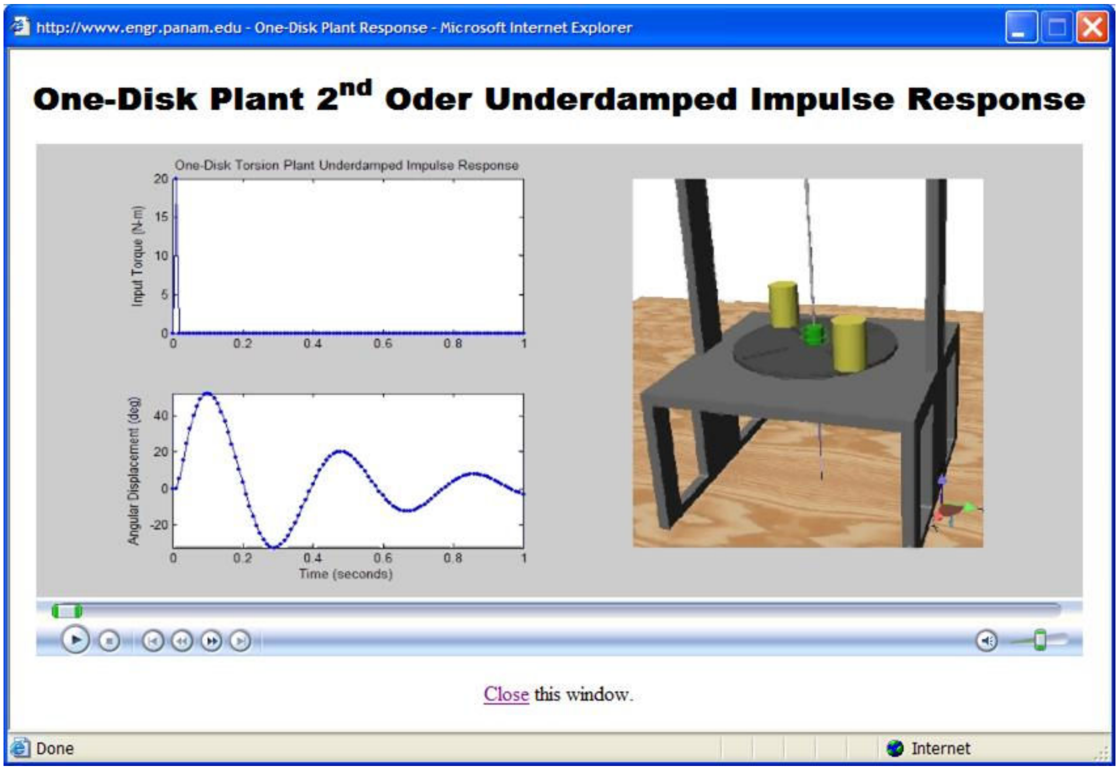

Figure 3: Animated response of a virtual torsional plant system.

Assessment Plan

Several assessment instruments are being employed to measure the impact of the laboratory formats being implemented. A System Dynamics Concept Inventory is being constructed with input from faculty at UTPA, UTSA and the University of Texas at Austin. Pre- and post-laboratory quizzes described below are being used to measure students' mastery of specific concepts. Additionally, surveys are being administered to assess students' perception of the laboratory modules and their utility in improving their conceptualization of specific fundamentals.

General Process and Procedures

The Teaching and Learning Center (TLC) at The University of Texas at San Antonio has been assisting with the development of our assessment plan. One of the core missions of the TLC is to provide programs and services that represent ways of expanding on traditional lecture-based approaches to instruction. These are designed to help faculty identify and make use of forms of instruction, which are likely to prove more involving and comprehensive for students. The TLC offers activities that include training in the use of team-learning techniques in the classroom, the creation of support groups for the use of educational technology, assistance in the design of performance-based, application-oriented measures of learning, and faculty-initiated proposals. Dr. James Lackey, the director of the TLC, has offered his expertise in helping the co-PIs formulate general educational constructs and specific outcomes for this project. These serve as a guide for developing assessment instruments, such as pre- and post-laboratory quizzes.

As shown in Figure 4, the assessment procedure consists of administering a pre-laboratory quiz to measure the student's prior knowledge of dynamics systems and controls concepts, which was acquired in the prerequisite theory-based course. The student then performs the laboratory experiment and later takes a post-laboratory quiz which tests the same knowledge as the pre-laboratory quiz. Correlations between similar questions are performed to determine the effectiveness of the laboratory exercise in helping the student achieve the desired outcomes.

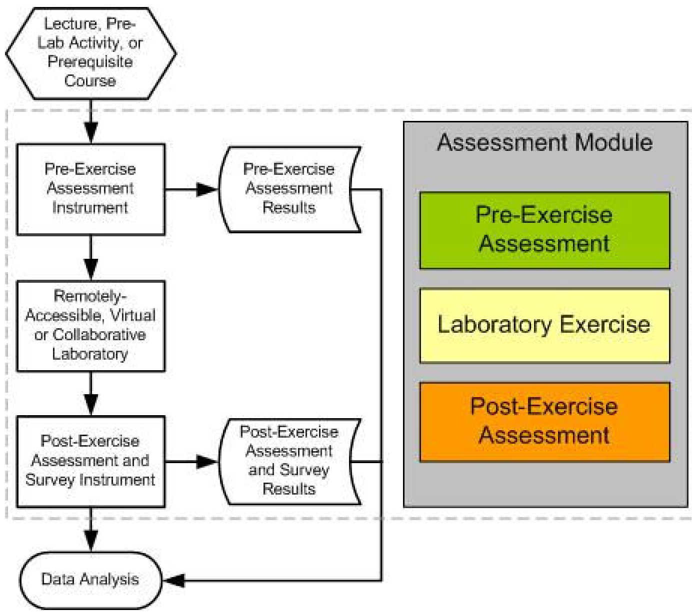

Figure 4: Assessment process.

Quiz questions are derived to measure specific *outcomes* that are linked to the *constructs* specified for each laboratory activity. The *constructs* comprise the overarching educational goals of the laboratory activity. The *outcomes* are measurable objectives that students should achieve as result of performing the activity.

Dynamic Systems and Control Concept Inventory

As part of the assessment process, a Dynamic Systems and Control Concept Inventory is being developed. The inventory is currently in its preliminary stages and the focus thus far has been on identifying those primary concepts that can be demonstrated using the previously mentioned systems that are readily available in the laboratories at UTSA and UTPA: the inverted pendulum, ball and beam system, torsional vibration plant, and rectilinear vibration plant. The initial step in formulating the concept inventory was identifying general subject matter categories as identified in Table 1. Table 2 lists the concepts specifically covered by the laboratories previously mentioned. Note that the concepts are linked back to the Subject Matter categories listed in Table 1.

Subject Matter Categories
1) Laplace Transforms 2) Transfer Functions 3) Nonlinearity and Linearization 4) Time Domain Analysis 5) Frequency Domain Analysis 6) Root Locus Analysis 7) Control System Design by Root-Locus Method 8) Control System Design by Frequency Response 9) Lead-Lag Compensation 10) PID Compensation

Table 1: Subject categories.

	Concepts
Torsional and Rectilinear Vibration Plants	4) Time Domain Analysis a) 1^{st} Order Responses i) Transfer Function ii) Impulse, Step, Ramp, and Free Vibration Response Identification iii) Time Constant iv) Physical Realization b) 2^{nd} Order Responses i) Transfer Function ii) Impulse, Step Ramp, and Free Vibration Response Identification iii) Damping Ratio iv) Damped and Natural Frequencies v) Overshoot and Settling Time vi) Physical Realization c) Higher Order Reponses 5) Frequency Domain Analysis a) Sinusoidal Transfer Function b) 1^{st} Order Responses c) 2^{nd} Order Responses d) Higher Order Responses e) Bode Diagrams
Inverted Pendulum and Ball and Beam System	3) Nonlinearity and Linearization a) Common Nonlinearities: sine, cosine, signum, etc. b) The Principle of Superposition c) Linearization i) Taylor Series Expansion of a Single Variable Function ii) Taylor Series Expansion of a Multivariable Function iii) Taylor Series Expansion of a System of Nonlinear Differential Equations 4) Time Domain Analysis a) Integral and Derivative Control Action b) Steady-State Errors 6) Root-Locus Analysis a) Root Locus Plots b) Positive-Feedback Systems c) System Stability

Table 2: Laboratory specific concepts.

Preliminary Assessment Results

A preliminary virtual system module was introduced to System Dynamics students at UTPA in the Fall of 2004. The module includes animated simulations like that illustrated in Figure 3 of the torsional plant systems depicted in Figure 5 (c) and (d). During lecture, students were taught basic analysis of 1^{st} and 2^{nd} order systems, using as examples the rectilinear plants depicted in Figure 5 (a) and (b). Additionally, students were taught how to derive responses using Laplace transforms and how to plot responses using MATLAB. Students were assigned a homework assignment on 1^{st} and 2^{nd} order systems. In a subsequent lecture, students were administered a Pre-Quiz on 1^{st} and 2^{nd} order responses. They were then assigned the virtual system module for the torsional plants depicted in Figure 5. Finally, they were administered a Post-Quiz.

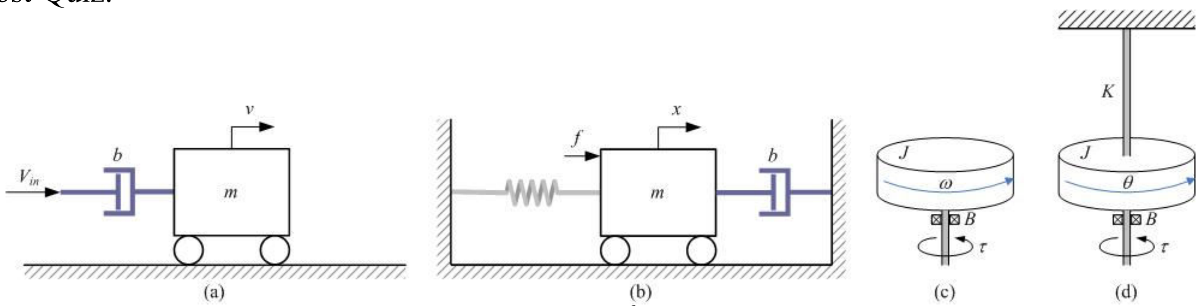

Figure 5: 1^{st} and 2^{nd} order plants.

The systems depicted in Figure 5 were used to demonstrate to students the basic concepts associated with analysis of 1^{st} and 2^{nd} order systems. The lecture and subsequent virtual system module activity were developed to address the following constructs:

- Enable students to effectively identify and characterize responses for 1^{st} and 2^{nd} order systems.
- Enable students to directly relate response characteristics to physical system parameters, such as mass, stiffness, and viscous damping coefficient.

The measurable outcomes are that the student should be able to successfully accomplish the following:

1. Determine the time constant for a first order response.
2. Identify the basic characteristics of a second order response including maximum overshoot, M_p, and settling time, t_s.
3. Determine the period of oscillation (T) for a second order response and relate it to the damped or natural frequency (ω_n and ω_d, respectively).
4. Determine the damping ratio (ζ) for a second-order response.
5. Associate a response with a physical system (e.g. the student will be able to associate an underdamped response with a mass-spring-damper system as opposed to a mass-damper or mass-spring systems).
6. Differentiate between the responses of first and second-order systems.
7. Distinguish between the various types of responses – free vibration, impulse, step, and ramp – for first and second order systems.

Based on the above constructs and outcomes, a Pre- and Post-Quiz were developed. The results of the Pre- and Post-Quiz were compared to identify any trends or improvements. As shown in

Table 3 students showed a marked improvement on 6 out of the 10 questions. Students showed improvement in only 1 out of 4 questions related to 1st order systems. This may be due to their familiarity with typical mass-spring-damper responses which are discussed throughout the Mechanical Engineering curriculum far more than simple mass-damper systems or other first-order systems. Additionally, students were administered surveys to assess their general impressions of the various tools used to demonstrate 1st and 2nd order system concepts. They were asked to rank lecture, MATLAB exercises, homework, and the virtual system activity in order for highest to lowest with regards to each activities impact on improving their understanding of the fundamentals. All listed the virtual system activity and the MATLAB exercises as their top 2 preferences. Furthermore, more than 80% of the students surveyed agreed that the virtual system animations improved their ability to visualize physical responses. When asked to suggest improvements, many students suggested incorporating more virtual systems with MATLAB-facilitated analysis to improve their understanding.

	Question	Measurable Outcome(s)	Concept(s)	% of Correct Answers		Improvement
				Pre-Quiz	Post-Quiz	
1st Order Response	1	1	4.a.iii	50%	42%	No
	2	7	4.a.ii	83%	42%	No
	3	5	4.a.iv	58%	67%	Yes
	10	6	4 & 5	83%	50%	No
2nd Order Response	4	3 & 4	4.b.iii & 4.b.iv	25%	83%	Yes
	5	7	4.b.ii	33%	42%	Yes
	6	5	4.b.vi	33%	50%	Yes
	7	4	4.b.iii	67%	67%	No
	8	2	4.b.v	58%	75%	Yes
	9	2	4.b.v	42%	67%	Yes

Table 3: Pre- and Post-Quiz results.

Future Plans

Our future plans comprise three main activities: (1) We will further refine the laboratory formats that have already been developed, based on student feedback and faculty evaluation of how well the laboratory activities were executed. (2) We will begin implementing the Inter-University laboratory format by developing the necessary educational materials, such as experimental procedures, delineation of student group tasks, protocols for interactions between the two campuses, and evaluation tools. (3) We will begin to investigate ways to automate pre- and post-laboratory quizzes and student surveys related the laboratory exercises. We hope to use existing tools such as Web CT or other software available on our respective campuses. This automation will enable the co-PIs to more efficiently tabulate student responses and recognize trends that point to the effectiveness of the different laboratory formats.

Conclusions

This paper summarized our progress to date in the implementation of new Web-based approaches to teaching undergraduates System Dynamics and Control Theory. We described three laboratory formats and how they can remedy existing challenges to improving student conceptualization of the essentials of these fields. We presented our preliminary assessment plan, including a concept inventory, and our findings based on our preliminary implementation of two laboratory formats. We are encouraged by our success in overcoming technical issues during implementation of the laboratory activities and our initial findings regarding improved student conceptualization. We look forward to reporting on the outcomes of our future plans and the dissemination of our approaches to the greater educational research community.

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