122nd ASEE Annual Conference & Exposition
June 14 - 17, 2015
Seattle, WA
Making Value for Society
Paper ID #11300

Virtual Laboratories Using Simulink: A Pilot Study

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Abstract

The use of laboratory exercises in engineering education, and in particular dynamic systems and control, has historical precedence for both increasing student understanding and maintaining student engagement. This paper describes the authors' development and implementation of virtual laboratories using Simulink 3D Animation. In this pilot study, virtual laboratories were developed based on two commercially available bench top laboratories, ECP-505 and ECP-210, which are a novel inverted pendulum design and a series mass-spring-damper system, respectively, and a simple cruise control model. Results are presented from a Spring 2014 implementation in which system identification and PID controller design were performed on the ECP-210 virtual laboratory. Descriptions of laboratory exercises are presented along with directions for future research, including improved assessment approaches and ideas for additional laboratory exercises.

Introduction

Despite the importance of dynamic systems and control in daily life, students are often not motivated to study those topics for various reasons. One source of student dissatisfaction comes from the mismatch between the complex robotic systems that are used to motivate the topic and the more mundane systems that are studied in-class. Typical dynamic systems and control courses focus on mass-spring-damper models of mechanical systems for in-class examples and simple hardware prototypes of these systems for laboratory exercises. This simplicity is useful because it allows the instructor to focus on essential understanding of the course material without unnecessary complexity; however, such simplicity leads students to wonder how to extend the concepts to more complex systems. Students also have difficulty visualizing the solutions to the differential equations that are ubiquitous in such courses[1]. Physical laboratories can help with student visualization, but there are practical limits to the number and variety of physical laboratories that can be given in a course.

Recent trends have shown the feasibility of teaching laboratory skills in the area of dynamic systems and controls through the use of virtual and remote laboratory environments[2]. While virtual labs have several drawbacks relative to physical laboratories, they also bring several advantages. Namely:

- Virtual laboratories are inexpensive. The cost to outfit laboratories in dynamic systems and control is high. In addition to the hardware cost there are associated costs in teaching assistant and instructor time to run the laboratory sessions. With funding to many institutions on the decline, virtualization of laboratories is a useful cost saving mechanism.
- Virtual laboratories can be incorporated into homework. This can lead to a credit hour reduction in dynamic systems and control courses; that credit can then be used to offer additional classes on emerging engineering fields.
- Virtual laboratories can model large-scale systems. Hardware laboratory plants are limited in size and scope by the laboratory environment. These laboratories also must typically be completed within a fixed time window. Virtualization allows students to work with large-scale systems such as airplanes and increases the complexity of labs by removing time restrictions.
- Virtual laboratories are ideally suited to online courses. The use of online courses in science and engineering is increasing, and one of the most difficult aspects of online course development is replacement of hardware laboratories. Ideally, virtual laboratories can achieve the same learning outcomes as hardware laboratories in the online environment. However, more work is needed to understand the extent to which the learning outcomes are achieved by virtual laboratories relative to their hardware counterparts.

The use of interactivity via laboratory exercises in engineering education, and in particular dynamic systems and control, has historical precedence for both increasing student understanding and maintaining student engagement[3,4,5,6]. Although the most common approach to using such systems for teaching and engaging students consists of traditional bench top systems, recent efforts have been made to reach students through their interests. Common approaches in this realm range from using aircraft simulators[7,8] and video games[9,10,11] to using interesting mechanical systems such as motorcycles and bicycles[12,13,14] for developing intuition.

While many traditional bench top systems[15,16,17] have been employed in the past (and are typically a preferred choice), such systems require large amounts of space and a multitude of equipment, both of which are a difficult hurdle for many institutions worldwide to overcome. Fortunately, due to widespread use of technology, many institutions have taken to "remote laboratories" for reenforcing techniques learned in the classroom[18,19,20,21,22,23,24,25]. The idea behind such an approach is that multiple universities have access to a single system housed in a common location. A "remote" lab is setup in such a way to provide video feedback for visualization, an environment for interactivity via the internet, and (in some cases) sensory feedback via haptic systems[26]. The idea of using remote laboratories then becomes an interconnected university system where each institution in the system may schedule time for use of such equipment at a remote location. In general, such a setup works well insomuch as network bandwidth and accessibility remain sufficiently large. However, when either is lacking, student engagement and understanding suffer dramatically[21,27].

Additional approaches to promoting interactivity for educational reinforcement of classroom concepts come from web-based learning. While remote labs contain a physical piece of hardware located remotely, web-based learning is an online tool used for increasing student understanding, i.e., it is strictly software-based. Such tools are common in the computing discipline for teaching concepts such as abstraction, object orientation, and even embedded systems[21,28,29,30,31]. While the addition of these tools into the classroom is generally very helpful, they rarely take the place of an actual laboratory exercise (whether it be remote or traditional).

The work in this paper is motivated by one specific type of web-based learning tool referred to as the virtual laboratory. While virtualization itself is not a new concept (i.e., the use of virtual lab instruments such as multimeters and oscilloscopes are widespread in engineering curricula[32,33]) the creation of entire virtual modules is a relatively new concept with little to no assessment on increased learning potential and broadening of understanding[34,35,36]. Our broad goals in this area are the design, development, implementation, and assessment of virtual systems for increasing understanding in dynamic systems and control education. Due to the widespread integration and usage of Matlab/Simulink into nearly all dynamic systems and control curricula, our virtual systems utilize Simulink 3D Animation to generate realistic 3D animations of dynamic system behavior. While it is not a part of the base Matlab / Simulink package, Simulink 3D animation is a common toolbox on university campuses. This paper presents our initial work in this field and consists of descriptions of three virtual laboratories and implementation results of a pilot study.

Virtual Laboratories

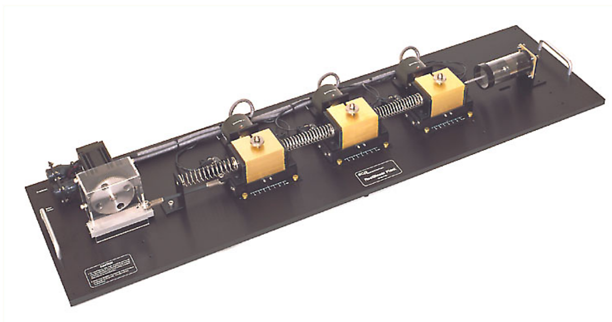
This section describes the virtual models that were generated along with the assignments that were given to students based on one of the laboratories. These models are available for downloading at http://webpages.sdsmt.edu/~mbedilli/STEM_Research.html for use by other instructors.

Modeled Systems

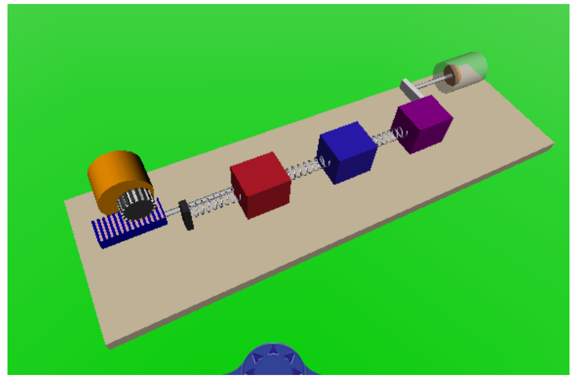
Two of the modeled systems are commercially available platforms from Educational Control Products[15]: the ECP-210 rectilinear plant and the ECP-505 inverted pendulum system. We targeted existing hardware laboratories so that students can eventually test controllers on the virtual systems before hardware implentation; however, this paper considers only the virtual laboratory aspect and not a coupled virtual / hardware implementation. The specific systems were chosen due to availability at the South Dakota School of Mines and Technology (SDSMT), but we plan to extend our example set to other commonly used hardware for applicability at other universities.

Figure 1 shows a Simulink implementation of the ECP-210 Rectilinear Plant[37]. The plant consists of a series connection of up to three mass-spring-damper systems and is commonly used to study vibrations and the control of flexible systems. While we have developed virtual laboratories for two and three mass systems, a single mass system was chosen for in-class implementation for simplicity. Two and three mass virtual models are more appropriate for a senior level control systems or vibrations elective, and we plan to introduce the virtual laboratories into those classes in 2015.

We have also completed a model of the ECP-505 inverted pendulum for use in a senior level control systems course[38]. The ECP design is unlike other inverted pendulum models in that the



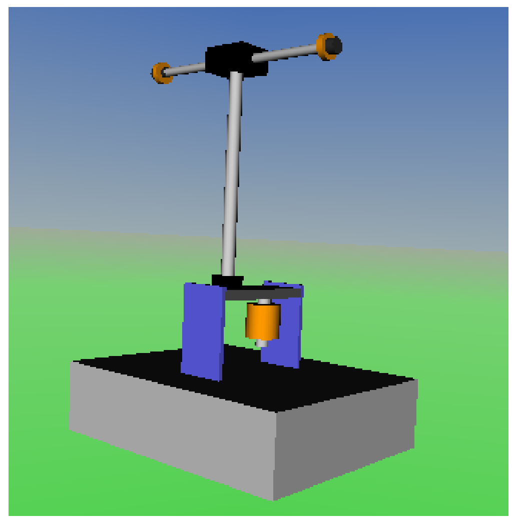
(a) ECP rectilinear stage[37]



(b) Simulink model of ECP rectilinear stage

Figure 1: ECP-210 rectilinear stage and associated model.

(a) ECP inverted pendulum[38]

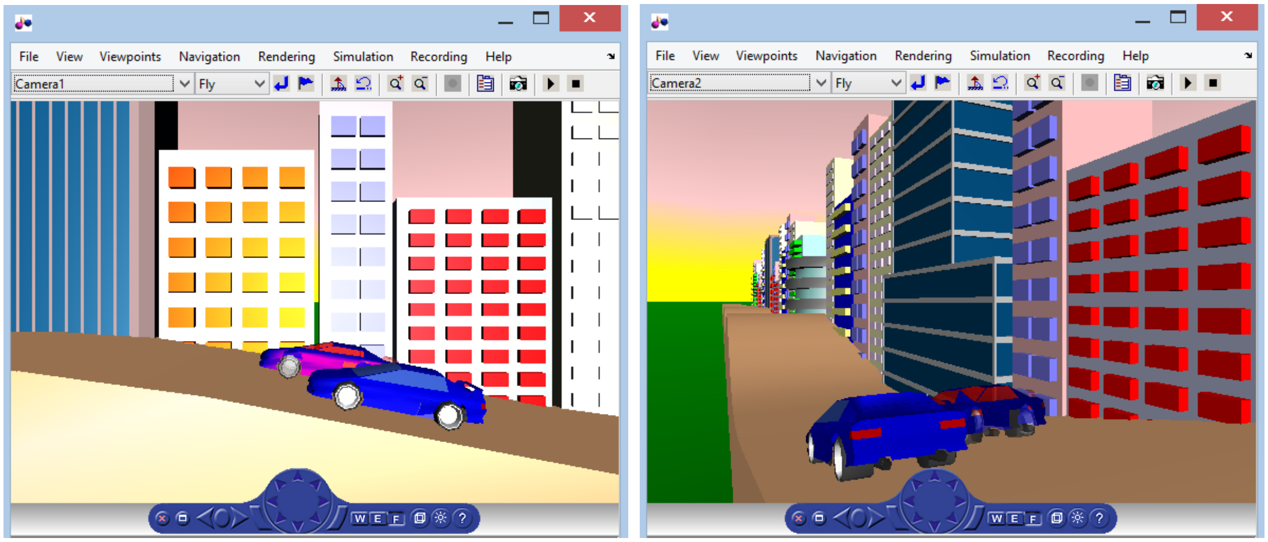


(b) Simulink model of ECP inverted pendulum

Figure 2: ECP-505 inverted pendulum and associated model.

pendulum is balanced by driving a rod back and forth at the top; this results in a difficult plant to control that is both unstable and nonminimum phase. The Simulink model of this inverted pendulum system is shown in Figure 2. Students will use this as a pre-lab exercise to test their controller designs before using the hardware equipment in SDSMT's Spring 2015 control systems elective, and this model will also be used for a class project on dynamics modeling and linearization in a future semester of the dynamic systems course.

The third system that was modeled was a simple cruise control system whose Simulink implementation is shown in Figure 3. Two cars are shown in the example: a solid blue car that is controlled by the student, and a semi-transparent purple car that moves at the constant desired speed. From a development standpoint this was the most difficult example. The sinusoidal road was generated in SolidWorks and imported into Simulink 3D Animation as a VRML model. We have generated models for various hill frequencies and amplitudes. In principle this example can be extended to any smooth road shape; sinusoids were chose for both ease of implementation and



(a) Standard view of cruise control example.

(b) Back view of cruise control example.

Figure 3: Cruise control example. The semi-transparent car moves at constant speed, whereas the solid car moves under the action of the cruise controller. The position difference between these cars indicates the controller error.

direct relationship to frequency response. Student exercises will focus on disturbance rejection and the effects of saturation in Spring 2015.

Anatomy of a Model

For our implementation, students are given a “black box” model at the top level to perform either system identification or control as shown in Figure 4. Students then add standard Simulink components to complete assigned tasks as discussed in the next section. The lock in the lower left-hand corner prevents students from seeing the contents of the subsystem. Making password-protected subsystems in Simulink is surprisingly difficult, so we rely on student apathy / inexperience by simply setting the block properties to prevent read/write access. This setting can easily be changed, but in our experience no student has done so.

A look under the subsystem’s mask reveals a simple structure: one subsystem is used to simulate the plant dynamics, and another uses the dynamics outputs to render the virtual reality scene (Figure 5a). A detailed view of the virtual reality subsystem in Figure 5b shows the complex structure of the scene even for this simple model. The position, angle, and scaling of each object can be changed based on the simulation parameters. For this model, the rotation of the pinion, positions of the mass, push rod, rack, and damper plunger, and scaling of the spring must be changed as the mass moves. Each of the subsystems in Figure 5b describes the geometric relationship between the motion / scaling of a component and the mass motion.

The development of the subsystems in Figure 5b consumes much of the virtual laboratory development time; the other major task is the development of the virtual world itself. Our approach was to use a combination of models available in Simulink 3D animation (e.g. the cars in

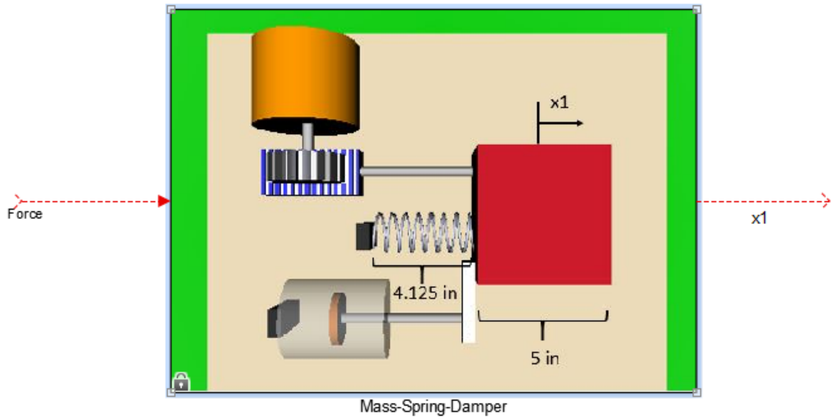
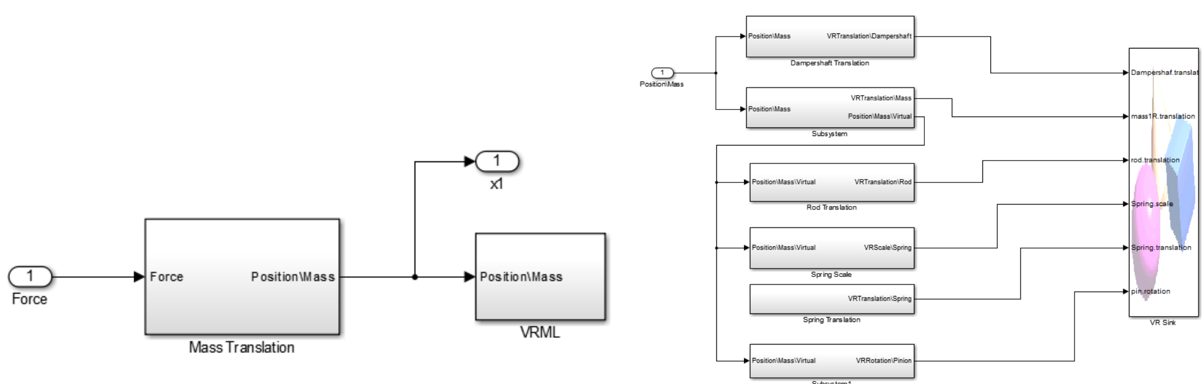


Figure 4: Student view of the ECP-210 one-mass model. The lock in the lower left-hand corner prevents students from looking at the contents of the subsystem block.



(a) Basic subsystem structure.

(b) Virtual reality subsystem.

Figure 5: Components of a model. Each model has a subsystem that handles the physics and a subsystem that manages the virtual reality rendering.

Figure 3) and imported geometry from SolidWorks (e.g. the rack, pinion, and spring in Figure 4). These elements and their connections form the virtual world, which is controlled through the VR Sink block at the right-hand side of Figure 5b.

Student Exercises

Virtual laboratories on system identification and root locus controller design were implemented in the dynamic systems course at SDSMT in Spring 2014. Combined performance on these two labs constituted 15% of the final grade. The student submissions took the form of formal memos with detailed calculations on engineering paper. Like conventional laboratories, each assignment included discussion questions for the students to answer in the memo portion. The learning objectives of these virtual laboratory assignments are to:

1. Introduce experimental system identification techniques. Much of the course focuses on first principles modeling, but system identification is much more common in practice. Students should be famililar with the basic methods of system identification starting with an assumed model form from first principles (e.g. first vs. second order dynamics).
2. Introduce feedback control concepts, specifically for PID controllers. Students should be familiar with the differences between open and closed loop systems, and the relative benefits of P, PI, PD, and PID controllers for reference tracking and disturbance rejection. The creation of such controllers in Simulink should prepare students to work with Simulink-based control prototyping environments, e.g. DSpace.

The system identification lab had students estimate the mass, stiffness, and damping of the system of Figure 4 using both step response and impulse response techniques. Detailed instructions were provided for generating impulses in Simulink via the difference between unit step functions offset in time. Students were also provided with refreshers on how step response and impulse response were related to natural frequency, damping ratio, and system gain. The system parameters used in the Simulink model are based on measured values from the hardware at SDSMT. While the initial implementation did not include variability in the data, future iterations of the exercise will include random purturbations to the measurements to mimic the uncertainty found in hardware system identification.

The second assignment was more involved and required students to design P, PD, PI, and PID controllers for the plant identified in the first assignment to meet various specifications. The proportional and PI specifications required students to find the gain needed to achieve a certain closed-loop damping ratio. The PD and PID controller designs provided overshoot and settling time specifications. In all cases, students were required to submit both open loop and closed-loop step responses to both reference and disturbance inputs.

Results and Discussion

The assignments discussed in the previous section were given to a class of 40 students in Spring 2014. Quantitative evaluation of the project's success was difficult. Our goal was to enhance students' understanding of practical applications in which a system model is not provided; however, students are not tested on this material, and the authors were not able to find a suitable validated concept inventory to use in this case. Given this lack of a quantitative analysis approach, qualitative data were captured to evaluate the project.

A stop / start / continue survey was used to gauge students' response to the overall class contents; 21 of the 40 students responded. The comments relevant to these laboratories are:

- "Assign projects similar to Labs 1 and 2 earlier in the semester. These really helped with understanding of the material, and helped with learning to use the tools in matlab and simulink to my advantage." (START)
- "Group projects. Or at least allow collaboration... I feel like this will improve learning on the projects." (START)
- "I want to say individual projects, but I can see how they're necessary." (STOP)
- "Simulink, Assigning homework and projects." (CONTINUE)
- "As for the projects section, I am in between expanding and keeping them as is." (CONTINUE)

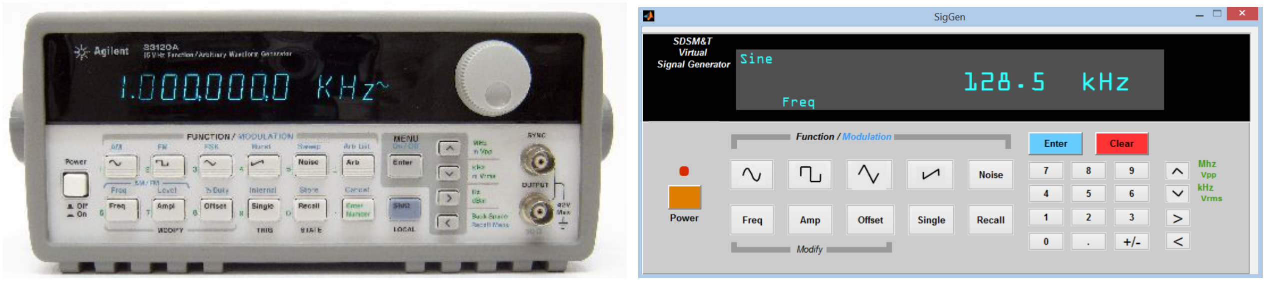
In addition to the open-ended questions, students were asked "Should this class keep the projects?" and given three options: "expand the projects," "keep as is," and "drop them completely." Of the 21 respondents, 6 (˜29%) said that the projects should be expanded, 14 (˜67%) said that the projects should be kept as-is, and only 1 (˜5%) said that they should be dropped completely.

Based on the student reponses to this pilot study, the projects will come back in improved form in Spring 2015. The cruise control example will be implemented in the dynamic systems course to vary the plant type under consideration. The ECP-505 virtual laboratory will be used in a combined virtual / hardware laboratory in the senior control systems elective and we are investigating use of the ECP-210 two-mass system into the senior vibrations elective.

Conclusions and Future Work

This paper has detailed a pilot study that uses Simulink-based virtual laboratories in dynamic systems and control. Two virtual laboratories were developed that mimic the behavior of commercial laboratory equipment along with a virtual laboratory of a cruise control system. These virtual laboratories are freely available at http://webpages.sdsmt.edu/˜mbedilli/STEM_Research.html. One of these laboratories was implemented in Spring 2014, with student feedback being generally positive. Follow-on work in 2015 will expand on this pilot project.

While results thus far have generally been positive, there is certainly room for improvement. One area that we are currently focusing on is introducing models of commercial measurement equipment (oscilloscopes, DSA's, function generators, etc.) into the virtual laboratories. Our intent is to prepare students for future classes or jobs in which actual hardware is used rather than



(a) Commercial function generator (b) Simulink implementation

Figure 6: Commercial function generator and corresponding Simulink model. The intent is to make students familiar with actual laboratory equipment through the virtual laboratories.

virtual learning environments. An early prototype of a function generator is shown in Figure 6 along with its inspiration.

In addition to adding virtual laboratory equipment, much more work is needed on evaluation. Improved qualitative survey designs will be developed and implemented in Spring 2015. We will also begin assessing whether the use of these virtual laboratories has any measurable impact on laboratory performance in follow-on control classes.

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