Embedding Simulink algorithms on hardware

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ABSTRACT: Dynamic systems modelling and control courses are often very mathematical and heavy on theory. The use of laboratory-based activities in these courses is not a new phenomenon, but the advent of new software tools have changed the way these courses can be taught. Today's engineering students should be provided with these tools to help them learn and understand the material more effectively. Simulink can be used to illustrate most of the topics commonly taught in dynamic systems and control courses without any programming. In this article, the author presents the use of Simulink from within a MATLAB environment along with a microcontroller to develop some experiments to improve student's understanding of the material presented in lectures and expose them to some practical considerations related to dynamic systems modelling and control.

INTRODUCTION

Modelling and control courses are often very theoretical and mathematically intense. Students often find the material too abstract, too mathematical and difficult to master when it is presented in lectures [1]. It is generally accepted that learners retain much more knowledge from direct experience than they do from the standard lecture format [2][3]. When a student builds some intuition for a specific topic, they are more likely to retain the information when compared with learning the material as a rote procedure. Activity-based learning can help in building this intuition [4].

Instructors always would like to incorporate experiments in these courses to make this abstract material concrete, and increase students' interest and understanding. Most of the experimental equipment involving feedback control experiments is often expensive [5]. At the same time, some educators have presented some inexpensive interesting experiments that require a kit/set-up that could be purchased for (or by) the student, such that they could be kept or borrowed by the students [6-8].

Many papers discuss how Simulink can be used as an effective teaching tool in areas, such as dynamic systems [9-12] mechanical systems [13][14] microcontrollers [15] and digital systems [16-19]. This article also presents some cost effective Simulink-based experiments to improve student's understanding of the material and deepen their learning.

BACKGROUND AND COURSE DESCRIPTION

At Grand Valley State University, Mechatronic System Dynamics and Control is a required junior level course taken by mechanical engineering students. It combines modelling, simulation and control of dynamic system. This course includes a theoretical part, where principles of system dynamics and system control are emphasised, as well as a laboratory part to emphasise theoretical knowledge with hands-on experience using real time control systems. Mechatronic System Dynamics and Control builds upon previous knowledge distributed in various courses, such as dynamics, differential equations, circuit analysis and digital systems. The students apply the collective knowledge from these courses to design and model electro-mechanical systems. Systems are modelled in time domain with differential equations. System analysis is done using different methods, such as transfer functions, state space, explicit solution of differential equations, numerical integration and Laplace transforms. Block diagram and Bode plots are then used for control system design and analysis.

The experiments that were used in this course in the past involved microcontroller (Arduino) and C programming. The students needed to write their own code in C to program the microcontroller. Many students struggled in programming and they spent most of the laboratory time in debugging their code and were not able to finish the laboratory in time. They were frustrated and since their focus was on making their code run, the whole objective of the laboratory was lost. The availability of computer simulation tools, such as MATLAB/Simulink allow the students to simulate, analyse and design engineering systems quickly and easily. Simulink can be used to illustrate most of the topics commonly taught in dynamic systems and control courses without any programming.

Recently MATLAB/Simulink has been introduced in this course. This was the first time students use MATLAB in this course. When MATLAB/Simulink was introduced to the students, they expressed that it was a fun, and an interesting tool for simulating dynamic systems. They also asked if the laboratories can be based on Simulink and not on programming. The author did some research if Arduino can be communicated with Simulink and found that it could be used with MATLAB and Simulink without the purchase of any extra toolbox. Earlier, the students used to do experiments that involved often costly equipment like a power supply, oscilloscope and function generator.

Simulink replaced the need of using these costly equipment and it replaced a function generator and oscilloscope in addition to serving as a simulation and algorithm development environment. Furthermore, the necessity of power supply can also be eliminated by using the Arduino board, which can supply power for small experiments. In laboratories, the students are required to submit a pre-laboratory, which includes modelling and simulation. During the laboratory, students construct systems, take readings and verify theoretical prediction with experimental results. The laboratory experiments serve to reinforce classroom material on first order systems, second order systems and feedback control. Two of the laboratory activities are described below.

TIME RESPONSE OF A FIRST ORDER SYSTEM - RC CIRCUIT

First order systems were covered in lecture a week before this laboratory. In the pre-laboratory, the students were asked to obtain the mathematical model of the electrical system shown in Figure 1 in terms of input and output voltages, calculate the explicit equation for the time constant by solving the differential equation, and find the DC gain and the steady state output. The mathematical model of the system is given as:

$$RC\dot{V_c} + V_c = V_i(t) \tag{1}$$

In the laboratory, the Arduino board is used for generating the input to the circuit and for measuring the output of the circuit. The input to the circuit is a 5 V step, generated from one of the board's digital outputs, applied across the resistor and capacitor. The output of the circuit is the voltage across the capacitor which is read via one of the board's analogue inputs. The students first create a Simulink model for the actual RC circuit system as shown in Figure 2. The input is connected to pin 8 of the Arduino, and the output is connected to pin A0.
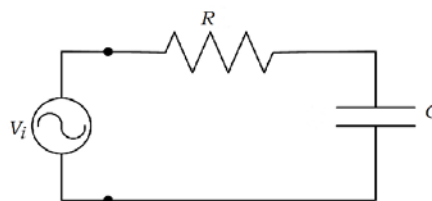

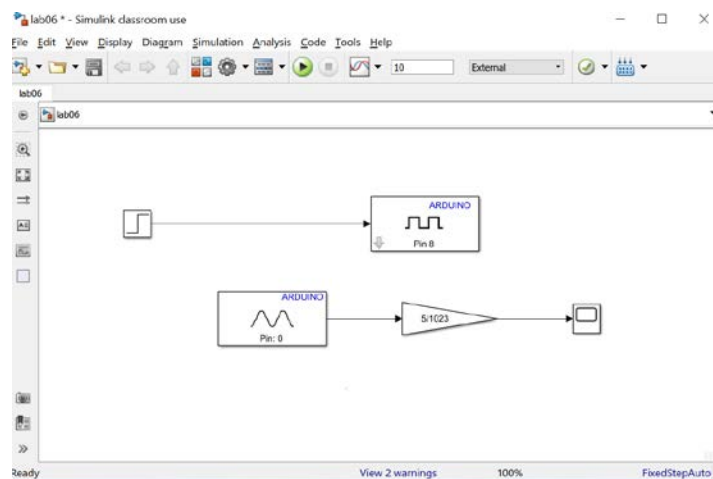Figure 1: A first order system - RC circuit.

Figure 2: Simulink model of the RC circuit.

Simulink is used to read the data from the board and to plot the data in real time. The model runs in external mode with hardware implementation board selected as Arduino Uno. The response of the system (output voltage) is shown in Figure 3. This data is then fed to Simulink for visualisation and for comparison to the resulting simulation model output, that is, the students then need to validate the circuit response by comparing the step responses predicted by the model, given by Equation (1), to the actual data recorded from the circuit (Figure 3).

Figure 3: The first order response of the RC circuit.

The Simulink model for the differential equation and the step response are shown in Figures 4 and 5. When comparing the responses in Figures 3 and 5, the responses look very similar. From the responses, the students calculate the dynamic parameter of the system which is the time constant. The students then use a different resistor to see the effects of changing resistor on the response of the system. The students change the coefficients in differential equation or transfer function representing the circuit, make a theoretical prediction, then verify the prediction with an experiment. They observe how changing the resistance may change the time response of the system.
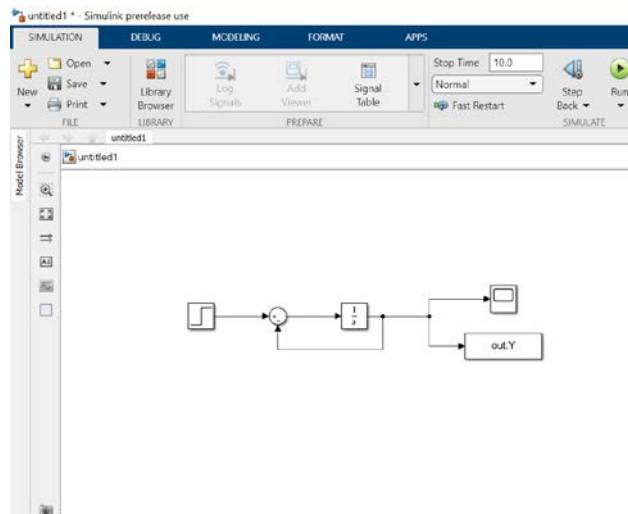

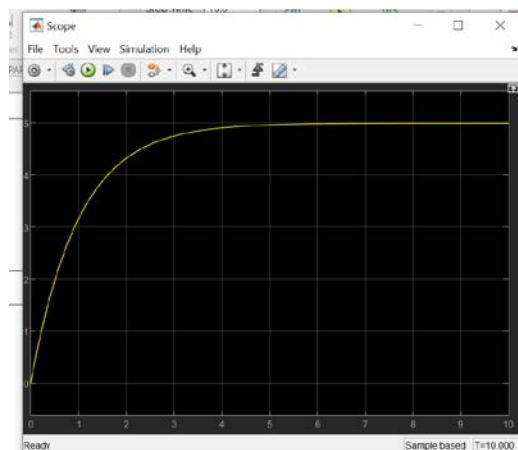Figure 4: Simulink model for the differential equation given by Equation (1).

Figure 5: Step response of the model.

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The above experiment is extended to an LRC circuit, which is a second order system, shown in Figure 6. As earlier, students are asked to obtain a mathematical model of the system and calculate the time domain specifications: peak time, settling time, damped frequency, damping ratio and overshoot from the response of the model. They are then asked to validate the model by comparing the step response predicted by the model to the actual data recorded from the circuit. They also need to replace the capacitor with a different capacitor and observe how the circuit's response changes with capacitance. They observe the effect of changing capacitance on damping ratio, overshoot, peak time, settling time and steady state.
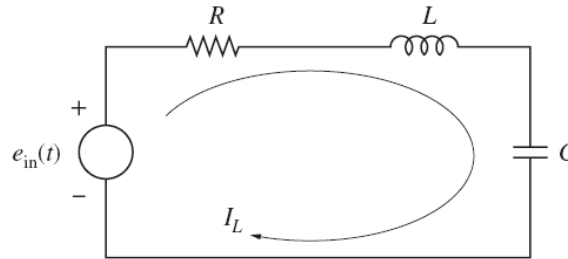

Figure 6: A second order system - RLC circuit.

The circuit shown in Figure 6 is built with the input connected to pin 9 of the Arduino, and the output connected to A5. A 1 H inductor with an equivalent series resistance of 40 Ω, 10 Ω resistor and a 100 µF are used to construct the circuit. A Simulink model, in external mode, is built to control the Arduino, so that it would provide the input voltage and collect the output voltage of the circuit in the form of a graph (Figure 7).
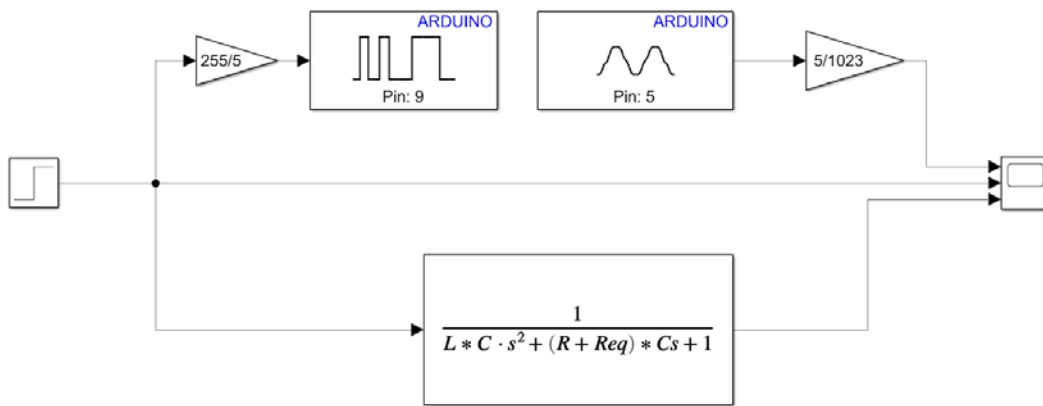

Figure 7: Simulink model to control the Arduino and simulate the circuit.

The input voltage is set at 4 V using a pulse-width modulation Simulink block. This is done to ensure that the Arduino could read the entire response voltage. The Arduino's range from 0 to 5 V, so if the input is set at 5 V, the Arduino would not be able to read the signal properly, if the overshoot is significantly greater than 5 V, due to the underdamping of the signal. Therefore, the input voltage of 4 V is used to make sure that the Arduino would read the whole response signal. After the Simulink model is run, the system's parameters, the natural frequency, damping ratio, damped frequency, peak time, overshoot and settling time, are calculated from the plot of the response, as well as theoretically from the system's mathematical model. The recorded response is then compared to the theoretical Simulink model given by the transfer block. The experiment is then repeated with a second capacitor of 510 µF.

The experimental and theoretical responses of the LRC circuit are shown in Figure 8. The rise time and peak time of the experimental results are then calculated from the graph. From these values, the natural frequency, damping ratio, damped frequency and maximum overshoot, are calculated. The experimental natural frequencies are greater than the theoretical value. The experimental results also has less overshoot, and has a smaller peak time and settling time. This again is due to variation in the inductance of the inductor from their nominal value.

The experimental response for the circuit is more damped than the theoretical response that means the theoretical response has more oscillations. This is likely because the actual inductance of the component used is different from the nominal values. Since the damping constant is larger for the experimental response, the inductance is likely smaller than its nominal value. This is also why the experimental response has less overshoot. It has been found that the specific model of the inductor used in this experiment is 1 H and this value is measured at a specific DC current. The manufacturer states in the data sheet that units will exhibit less inductance at slightly higher currents and more inductance at lower currents. The inductor used in this experiment has a rated DC current of 240 mA, whereas the highest current in the LRC circuit during the time considered is found to be less than 60 mA, which is one fourth of the

rated DC current of the inductor used. This means that, based on the information provided by the manufacturer, the inductor in the circuit will exhibit a significantly different inductance than the stated 1 H value, which is shown by the discrepancy between the actual and theoretical response.
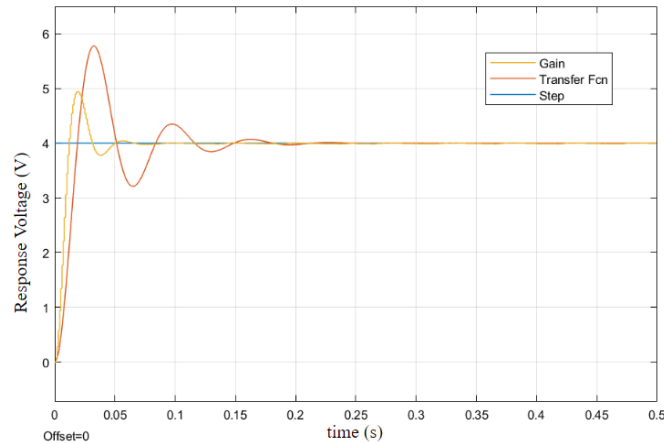

Figure 8: The theoretical and experimental response of the LRC circuit with a 100 µF capacitor.

CONCLUSIONS

Computer simulation is a vital part of any course involving moving systems. The ease of programming in Simulink facilitates its use in undergraduate engineering education. In this article, the author presented the use of Simulink together with a microcontroller to develop simple experiments to reinforce theoretical concepts with experimental validation. The laboratory activities presented allowed for the study of the system parameters through experiments and predicting the parameters through theoretical calculations.

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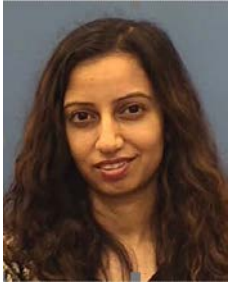
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