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A Low-cost Laboratory Experiment Setup for Frequency Domain Analysis for a Feedback Control Systems Course

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Abstract: Increasing need in automation systems increases the need for control engineers that have practical experience from their undergraduate education. Having abstract mathematical concepts and condense theoretical materials, Feedback Control Systems classes are not generally well-comprehended by undergraduate students. In this paper, we propose a low-cost laboratory setup for Feedback Control Systems education to support learning of frequency domain characteristics of LTI systems. The proposed setup works based on identification and control of a DC motor and includes Matlab interface to be programmed by high level control design tools such as Simulink. This paper shows how students can experimentally validate the concepts like Bode plots, gain margin, phase margin and delay margin.

Keywords: Control education, laboratory setups, arduino, system identification, frequency response, time delay.

1. INTRODUCTION

Feedback control systems has a wide application area in both academia and industry. The deep theoretical content as well as the requirement for regularizing outputs in most systems make the area applicable to various problems from different research disciplines. On the other hand, the abstract mathematical content results in a deep learning curve, which makes it difficult for students to establish an analogy between the theory and the real life problems.

Nowadays, with increasing need in automation technology, industry seeks for expert control engineers, who can adapt and implement the Feedback Control Theory solutions to various real-world problems. To accomplish this, curriculums in engineering, especially Feedback Control Theory classes, should be updated to include more experimental experience as a part of their education methodology (Goodwin et al., 2010). In fact, importance of practical experience in engineering curriculums has been a long debated issue (Kheir et al., 1996). Besides, laboratory experiments is one of the fundamental requirements in ABET accrediated engineering curriculums (ABET, 2012).

One of the key functionalities of laboratory experiments is to support students' learning for fundamental concepts based on educational needs of instructors. However, note that it is not feasible to cover all topics in a laboratory session. Therefore, such experiments should be carefully designed to emphasize the desired topics based on the course curriculum. For example, laboratory experiments in Feedback Control Theory classes generally focus on investigating the abstract concepts such as stability, controller design and frequency response. Experimental inquiry of such concepts increases students' ability to comprehend the materials as well as develops their practical experience.

There are various ways to support student learning via laboratory experiments. However, all such methods can be mainly divided into two categories as virtual and real experiments. In virtual experiments case, each section in the experiment is performed in computer environment. Such computerized experiments can be further classified as simulations and emulations. In simulations, input–output representations of physical systems are used as plants to solve feedback control theory problems. On the other hand, emulations are more advanced versions of simulations, since nonlinear components of employed plants are also modeled in them, so that students get experience in working with realistic plant models (Goodwin et al., 2010).

Different than their virtual counterparts, real experiments include physical components and can have different realization levels like benchtop experiments, remote laboratories and pilot plants. As the realization level increases, the learning benefit and the cost also increase. Although the highest educational benefit can be obtained with pilot plants (Goodwin et al., 2010), they are not affordable for most colleges. For this reason, remote laboratories and benchtop experiments become more favorable options for most engineering colleges. Remote laboratories become popular with the spread of internet and they successfully bring low-cost solutions for laboratory experiments (Reguera et al., 2015; Kalúz et al., 2014). However, working with a remote hardware does not give the feeling of working with a physical system. Besides, operational and safety issues limit the learning outcomes (Goodwin et al., 2010). Therefore, benchtop experiments become an

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optimal choice for engineering colleges to obtain maximum educational benefit at an affordable cost.

Unfortunately, commercially available benchtop experiment kits also present expensive solutions, especially if the goal is to give a laboratory setup for each student. One advantage of such kits are their interfaces for easy programming of the desired control problems (Quanser, 2013). Otherwise, the electromechanical architecture is generally simple to build for most examples. Motivated by these problems, we adopt Matlab/Simulink interfaces with simple micro-controllers to design a low-cost laboratory setup for Feedback Control Theory classes. The proposed lab setup is easy to program by students via Simulink's block diagram interface and low-cost to build for any college around the world. In this paper, we show how difficult concepts in control theory such as frequency response, gain and phase margins can be observed experimentally by using this simple laboratory setup.

2. OVERVIEW

2.1 Students' Background

The laboratory experiment kits are designed and built to be used in EEE342 Feedback Control Systems course, which is a third year course in Department of Electrical and Electronics Engineering curriculum of Bilkent University, Turkey. This course is an introductory class to the area of feedback control systems and includes fundamentals of mathematical modeling of dynamical systems, analysis of open/closed loop systems, their characteristics and performance analysis, stability, root locus and frequency response. The frequency response part covers almost half of the curriculum, since it is respectively a more complex topic. In this part, students learn the Bode plots, gain and phase margins, Nyquist plots and lead/lag compensators.

Prior to this course, students are required to take EEE321 Signals and Systems and MATH242 Engineering Mathematics II courses. Thus, students will have the basic knowledge on differential equations, Laplace and Fourier transforms as well as frequency domain analysis.

2.2 Desired Learning Outcomes: Theoretical Experience

EEE342 Feedback Control Systems course has three independent laboratory assignments in a one-semester class. Our goal in this study is to design a laboratory assignment to support students' learning in frequency domain analysis. Some of the topics that are investigated with the proposed laboratory setup are listed as follows:

- Bode plots and frequency domain analysis of LTI systems
- Stability analysis in frequency domain
- Gain margin, phase margin and delay margin
- Time delay and its effect on frequency response plots

An ideal laboratory assignment should be designed to relate theoretical concepts that are explained in class to physical experiments to support students learning by experimental inquiries. Therefore, our desired learning outcome here is to emphasize the above listed concepts and strengthen students' learning for these topics.

In previous offerings of EEE342 Feedback Control Systems course, students are used to perform simulation-based experiments for investigating the feedback control theory problems. Unfortunately, designing controllers for transfer functions in simulation and observing the responses only in data does not yield the impact of working with a physical system. Especially, the abstract concepts such as frequency response require a solid understanding that needs to be supported by practical experience.

2.3 Desired Learning Outcomes: Practical Experience

Working with physical components definitely help students to gain experience with hardware and it increases students' self-confidence for working with physical components for their future projects. Therefore, the learning outcome in our experimental setups can be summarized as to support students' learning by exposing them to physical control systems problems and increase their self-confidence for practical experience.

In Bilkent University, we have nearly 200 students that take Feedback Control Systems course in a specific semester. Therefore, we decided to build 100 laboratory setups, which can be used by 200 students when they are working in pairs. Note that working with a group-mate both supports team work and decreases student's effort for dealing with a physical system during the experiment.

Another important issue here is that EEE342 Feedback Control Systems class is quite different than a micro-controllers or embedded systems course. Therefore, we aim to decrease students effort on micro-controller level programming, since the goal of these lab experiments are to support students' learning for Feedback Control Theory topics. Therefore, our main criterion in this step is to build a simple, low-cost laboratory setup that will support students' investigation on different feedback control theory topics such as frequency response without distracting their attention with the details of embedded programming.

3. THE LOW-COST LABORATORY SETUP FOR FEEDBACK CONTROL SYSTEMS EXPERIMENTS

In this section, we introduce the proposed low-cost laboratory setup that supports practical realization of the desired course topics such as analysis of frequency response characteristics. We utilize a DC motor with an encoder as our hardware plant in this system since most of the concepts in the course content can be simply implemented and illustrated on a DC motor application. The encoders on the DC motor is used to measure the rotation of the DC motor, so that we can compute the angular position and speed. To accomplish this, we use a micro-controller and a motor driver to both generate necessary control signals for the DC motor and to measure its rotation. In addition, an interface to a computer is required, so that we can program the laboratory setup to measure and observe the outputs.

3.1 Software Architecture for the Experimental Setup

In the design of the our laboratory experiment setup, we first determined some design decisions to choose the optimal, low-cost solution in the market. Our main decision criteria are as follows: