Teaching Classical Control to Mechanical Engineers via Take-Home Experimental Setup Based on Microcontrollers

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I. Introduction

Supplementing a control systems class with a hands-on experience for students by working on a real dynamical system helps in better understanding the classical control theory and emphasizes the importance of its applications. For a small size class this could be achieved by developing laboratory setups with various experiments that students can perform in groups taking turns. Many universities have already added a laboratory to their programs and have reported the beneficial effect of that for the students [3, 4]. In most cases they rely on commercially available laboratory setups [5]. Even then, finding suitable times that can accommodate all students might be difficult and it brings the necessity of a room and an instructor for the sessions. Solutions for those problems have been proposed by utilizing remote access laboratories via the Internet [6]. However, this would require additional equipment for remote access and still keeps the need for a specific room.

At the Aerospace and Mechanical Engineering Department of The University of Arizona, it is not unusual for the Control System Design course to have enrollment of about 100 students. This makes offering a lab section with the course nearly impossible. As a way to avoid canceling the practical experience of the course, we developed an inexpensive and portable setup, which can be taken home by the students, and they can work on it as their term project. Besides addressing our organizational problems, this solution brought an opportunity to demonstrate to students a modern approach towards control systems using computers and implementing the controller in software.

II. Experimental setup description

The setup consists of a small DC electrical motor, operating at 0-5V, attached to one of the ends of a light carbon rod. The other end of the rod is attached to an extension of the shaft of a low-friction potentiometer. The potentiometer is fixed on a plastic stand at the proper height, so that the pendulum can swing freely. A 2” propeller U-80 is attached to the motor shaft to produce a thrust force in order to control the angular displacement of the pendulum from the vertical position (fig. 1). A custom designed circuit board produces the controlled voltage supply for the motor via Pulse-Width Modulation (PWM) with a resolution of 0.05V, and reads out the voltage on the potentiometer, which is proportional to the angular position of the pendulum. These functions are implemented using a Microchip PIC16F690 microcontroller, mounted on a ZIF socket for convenient replacement in case of damage or reprogramming of firmware if needed (fig. 2). The microcontroller communicates with a PC through its serial port using RS-232 protocol and a Maxim MAX232 driver/receiver. It sends to the PC the value of the potentiometer voltage, measured by the built-in Analog-to-Digital Convertor (ADC), and receives the computed control signal and converts it to the respective PWM output for the motor. The PWM output is passed to an H-bridge configuration of MOS transistors, which produces the necessary current for the motor and allows bi-directional motor control [1, 2].

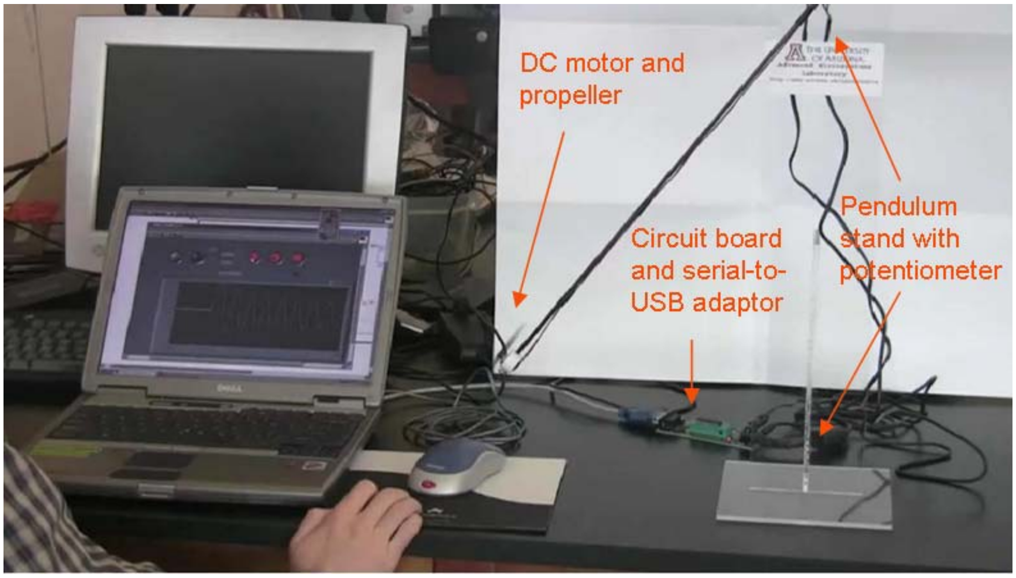

Fig. 1: Overview of the DC motor pendulum setup

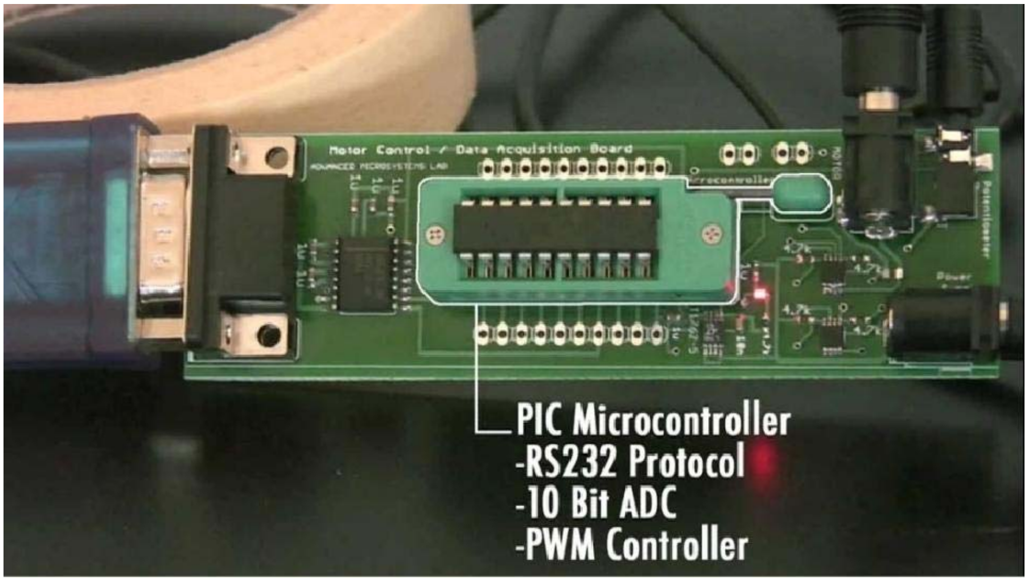

Fig. 2: Circuit board controlling the motor and reading the potentiometer voltage

A MATLAB program running on the PC receives the potentiometer voltage and computes the angular position of the pendulum from it. Then, the program either sends a constant control signal, in case of an open loop run, or computes and sends a proportional control signal in the case of a closed loop run of the experiment. It also plots in a figure on the computer screen the value of the displacement angle vs. time (fig. 3). A software module based on LabVIEW is also developed, to make the setup usable with this environment for educational institutions that have license for it only. More information could be found in [7].

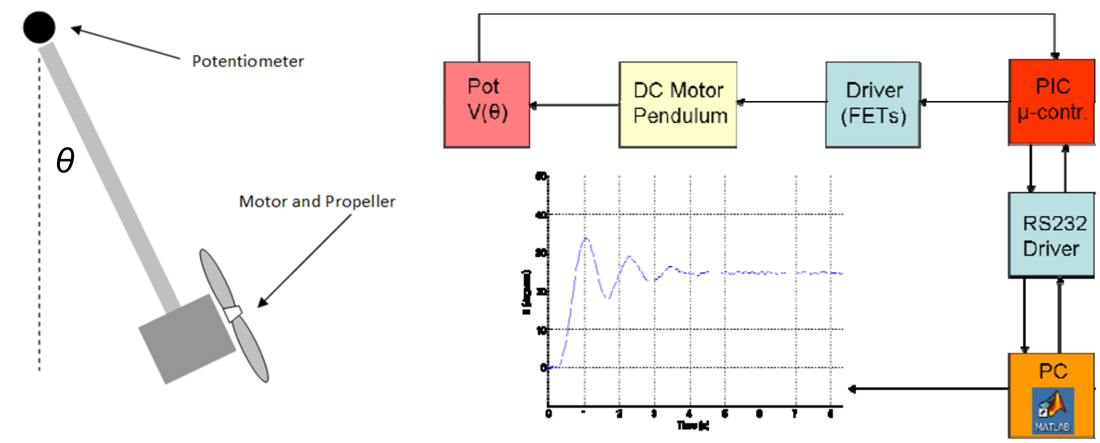

Fig. 3: Sketch and block-diagram of the setup

III. Project assignment description

The students develop a full (non-linear) mathematical model of the system and identify its physical parameters (the values of u_0 and K/mg on fig. 5). The latter are extracted using the open loop response of the system, illustrated in fig. 4. The system allows demonstration of non-linear effects occurring in the DC motor (due to dry friction) illustrated in fig. 5, and in the equations of motion of the pendulum (the sine term). Over the course of this experiment, the students also apply the method of feedback linearization by removing the sine term from the equations of motion of the pendulum (by including it in the computed control signal).

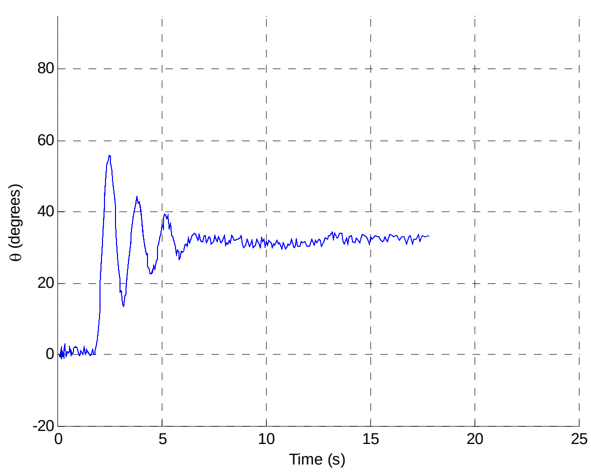

Fig. 4: Open loop response

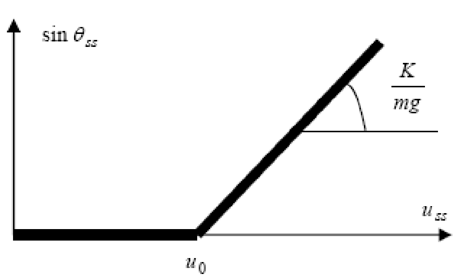

Fig. 5: Sine of the steady-state displacement angle vs. motor voltage

For the linearized closed-loop system, students are asked to determine how well it matches the theoretical predictions for steady-state error (based on the system type), disturbance rejection, and stability (based on the root locus of the system). Disturbance rejection properties are demonstrated in the closed loop response in fig. 6.

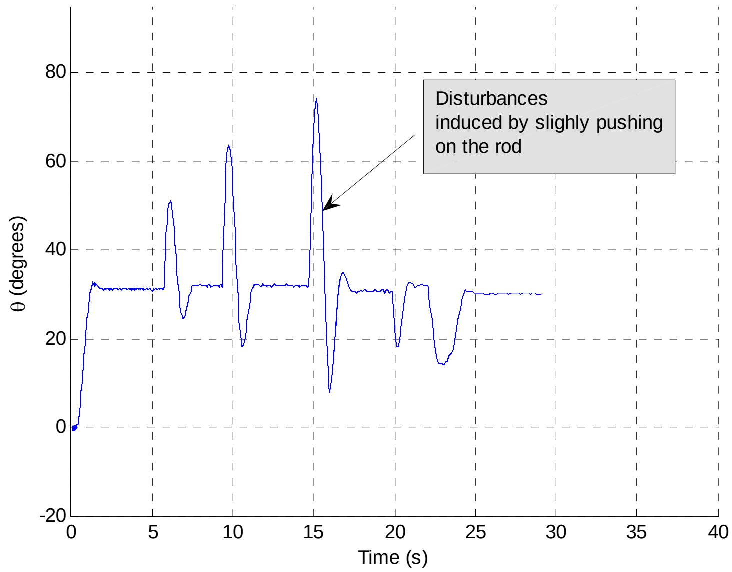

Fig. 6: Closed loop response

IV. Student experience assessment

During this semester, a paper-based project was also offered. A total of 72 students selected the hardware-based project, and 27 chose the paper-based one. An anonymous survey was conducted for the students choosing the hardware-based project, to share their experience after the first semester this project setup was offered in the Control System Design course, following the protocol approved by the Institutional Review Board. A total of 26 students participated and Table 1 shows the evaluation of technical contents of the project.

Table 1

To what extent (how well) did the project illustrate the following technical concepts?					
	Not at all	Less than expected	More than expected	Very well	Rating Average
Relation between physical system and transfer function	0.0% (0)	15.4% (4)	**50.0% (13)**	34.6% (9)	3.19
Second-order system response	0.0% (0)	15.4% (4)	**53.8% (14)**	30.8% (8)	3.15
Relationship between stability and gain	0.0% (0)	11.5% (3)	**46.2% (12)**	42.3% (11)	3.31

Table 1, cont.

To what extent (how well) did the project illustrate the following technical concepts?					
	Not at all	Less than expected	More than expected	Very well	Rating Average
Relationship between overshoot and gain	0.0% (0)	30.8% (8)	**42.3% (11)**	26.9% (7)	2.96
Use of root locus	0.0% (0)	38.5% (10)	**42.3% (11)**	19.2% (5)	2.81
Use of Bode plots	**50.0% (13)**	26.9% (7)	19.2% (5)	3.8% (1)	1.77
System type and steady-state error	0.0% (0)	19.2% (5)	**57.7% (15)**	23.1% (6)	3.04
Disturbance rejection and system recovery	0.0% (0)	30.8% (8)	**53.8% (14)**	15.4% (4)	2.85
Non-linearity and ways to deal with it	0.0% (0)	**42.3% (11)**	30.8% (8)	26.9% (7)	2.85
Effects of time delay	0.0% (0)	38.5% (10)	**46.2% (12)**	15.4% (4)	2.77

In a second part of the survey, we asked the students why they had chosen the hardware project over the paper-based one. The majority of them were excited by seeing the effect of the application of control theory to a tangible system. They were also interested in establishing a connection between the calculations and the experimental results. Here are some quotes of the actual answers: “I was excited about the idea of actually seeing this design work on paper get implemented into a tangible mechanism. It was very motivating. It answered the timeless questions, "Why do we need to know this? What is it good for?"”; ”The hardware project offered a more real-world physical representation of control system design.”; ”I like to be hands-on, I learn more from doing things with my hands.”; “It seemed more interesting to be able to apply the topic to a physical system rather than a theoretical controller design.”.

To the question where did the students do their experiments with the setup (how portable it is), most of the answers were at home or at the university computer labs. The need for lab or assistance during the project was assessed by the students participating in the survey in the following categories shown in table 2:

Table 2

Did not need a physical lab at all, I could do everything myself	56 %
Had to use the TA a bit, but 1 hr per week was enough	32 %
I needed to ask for additional assistance outside the 1 hr/week from the TA/instructor	8 %
The project should be done in a permanent lab with fixed operating hours and TA-s	4 %

V. Conclusion

An inexpensive (less than $100) take-home experimental setup has been designed for a hands-on experience of mechanical engineering students with a real control system. This makes it suitable for a term project, where minimal or no supervision is required, and no special time or place is needed. It also helps students whose major is not electrical engineering to become familiar with the modern developments in implementation of real-time control systems.

Acknowledgements:

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References:

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