Dual-Solenoid, Closed-loop, Position Control System

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Abstract

This paper presents a closed-loop, position control system, using two interconnected, DC solenoids in a pull-pull arrangement, and controlled by an Allen-Bradley, MicroLogix 1500 LRP, Programmable Logic Controller (PLC). This PLC, and similar equipment possessing A/D and D/A modules, are excellent vehicles for teaching closed-loop control, since they are easy to program and do not require a substantial background in programming. This feature makes it very attractive since our control classes and laboratories are populated by students from mechanical, manufacturing and electronic backgrounds. In addition, this particular PLC has built-in data acquisition capabilities, making it ideal for comparing theoretical responses (obtained by simulating a SIMULINK-based model) with that of the actual hardware. Further, PLCs are extremely common in industrial and manufacturing environments, and the student's familiarity with them can serve as an added bonus in seeking employment. This paper presents the modeling, parameter estimation, and simulation procedures. The setup can also be easily modified so that it is controlled by other types of controllers (microcontroller-based, PC-based controllers such as LabVIEW. This set-up can also be used by graduate students to investigate second-order-type effects. This hardware has been effective in enhancing student understanding and retention of control system theory.

Introduction

The teaching of control systems is enhanced by supplementing the lecture material with laboratory activity. The laboratory activity should reinforce the theory presented in class by providing a platform in which the theory can be applied. This paper summarizes a series of laboratory activities dealing with a closed-loop, position control system that utilizes dual DC-solenoids as the drivers, and PC as the controller. This work is an update of a similar position control system that utilized a single DC solenoid and an op-amp circuit as the controller [1].

What has prompted the changes from the previous implementation? The main one is the industry shift to use Programmable Logic Controllers (PLCs) rather than custom analog circuits for low-number applications. This is primarily due to:

a) increase in labor costs

b) decrease in PLC cost
c) decrease in number of personnel capable of working with electronic analog circuits
d) added flexibility that results from control implementations that depend on software rather than hardware
e) increased level of reproducibility that results from digital approaches (instead of analog ones)
f) many of the users of control systems (and students in the class) do not have an electronic background. The PLC provides an environment in which this background is not necessary.

At Arizona State University East (soon to be ASU Polytechnic) two control courses are offered. The first course covers modeling (electrical, fluid, mechanical and thermal systems) and classical control. The second one deals with digital control, state-space and some of the advanced features of MATLAB/SIMULINK.

In addition, we also offer four PLC-related classes in collaboration with the Mechanical and Manufacturing Engineering Technology Department. This particular experiment is used to introduce the PID concept, in one of these classes. Here the modeling and simulation issues are not covered.

The material that follows provides a snapshot of the laboratory experience that the students encounter. For a complete description of the process, the reader is referred to the complete lab book [2]. The rest of the material is covered in most feedback control texts [3-5].

Problem Statement

The problem is presented to the students as an assignment to a newly hired control engineer. A special effects company want to have a mechanical driver designed and built that will move the jaws of a plastic figurine that will be used in a in a children's movie. The jaws, shown in Figure 1, can be activated by moving a plastic rod relative to encapsulating flexible tubing. To swing the jaws through its entire range of motion, the flexible rod must be moved ½".

The students are initially given freedom to propose whatever schemes they choose. After they have suggested several approaches, if they haven't suggested using a DC solenoid, they are steered in that direction. At this point, they are given the assignment to investigate the characteristics of DC solenoids, with the expectation that they will realize that most solenoids only pull in their plunger (rather than push it out). Afterward, they are given two choices: a) a solenoid working against a spring and b) two solenoids in a pull-pull arrangement, as seen in Figure 2. After they have explored the possibilities, they are again steered to select the dual solenoid approach.

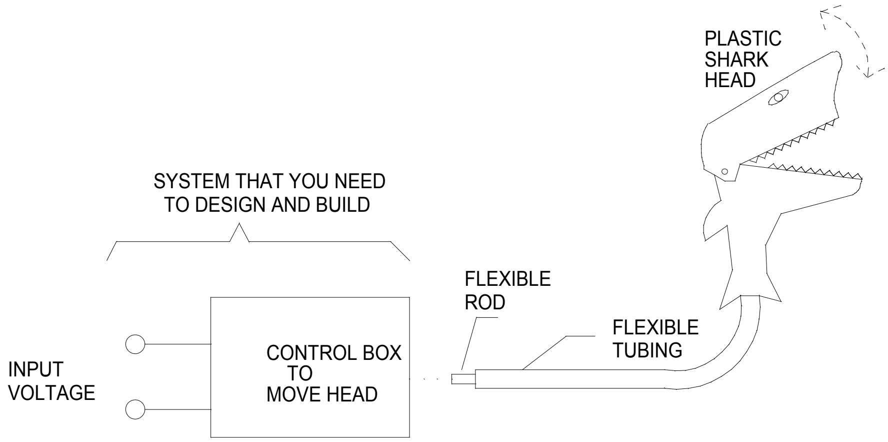


Figure 1: Proposed Application

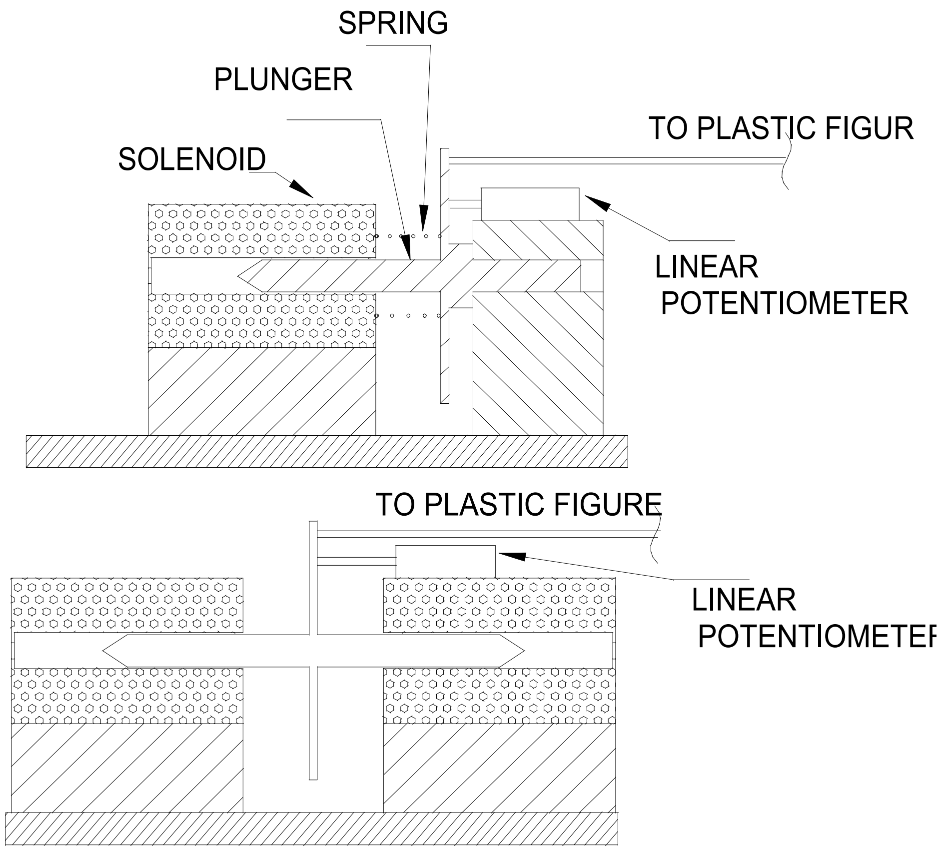


Figure 2: Single and dual solenoid implementation

Driving of Solenoids

The topic of how to electrically drive a solenoid is one that requires review. Most students realize that solenoids require significant current; consequently the driving circuit is not trivial.

Since some students from the Department of Mechanical and Manufacturing Engineering Technology populate the class, this aspect of the modeling process is not emphasized. There are several ways of driving the solenoids. They are:

a) using a modulated voltage (PWM)
b) using a varying analog voltage
c) using a varying analog current

The last approach has been chosen since it reduces the number of lags in the loop. In other words, having the driver circuit that produces current is preferred over having the driver circuit that produces a voltage (since there is a lag between applied voltage and resulting current). Note that the pulling force produced by the solenoid is primarily proportional to current. However, it should be mentioned that the resulting solenoid's force is not only a function of current, but also of plunger position. That is, when the plunger is almost out of the solenoid housing, it produces a much smaller force than when the plunger is almost all the way in. However, since we assume that the range of movement is relatively small, we assume that current-to-force coefficient ($\partial F / \partial I$) is constant around the operating range.

Thus, the driver circuit used to excite the solenoid converts the voltage produced by the D-to-A of the PLC (V_PLC_out1) into a current. This circuit is shown in Figure 3, has a gain of 0.8 A/V. Notice that it is, by itself, a closed-loop subsystem since it applies whatever voltage necessary to produce the desired current. It should be pointed out to students that the op-amp used (TI/Burr-Brown OPA549) is a very uncommon device since it can produce up to 10A (most op-amps can only produce 50mA).

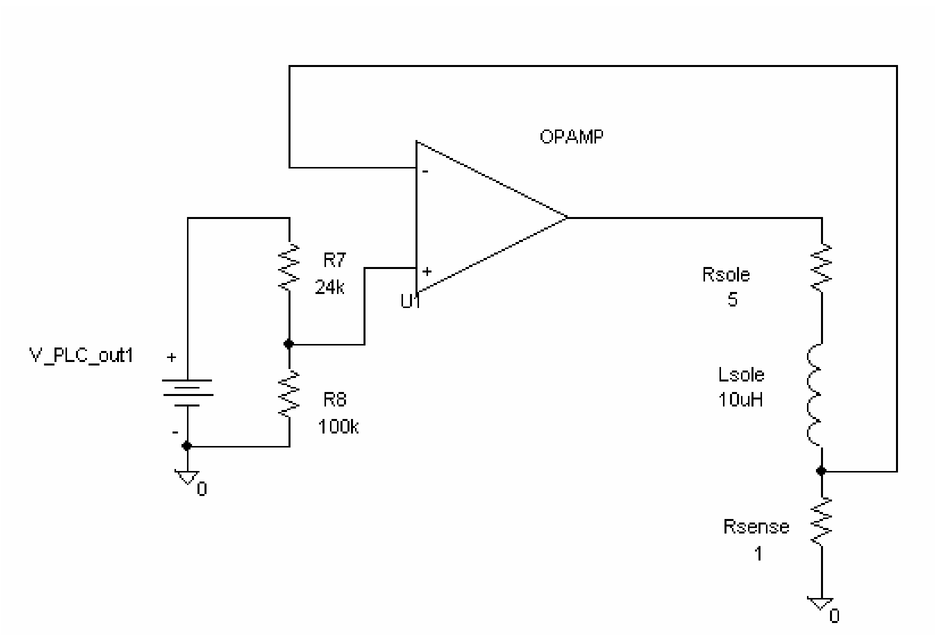


Figure 3: Circuit used to convert voltage into current. It uses the TI/Burr-Brown op-amp OPA549.

Modeling

The next task is to model the entire system. It is the author's opinion that the ability to represent a piece of hardware with a series of interconnected transfer functions in a block diagram is one of the most useful skills learned in a control class. The students are encouraged to propose descriptions for each of the subcomponents in the system (plant, sensors, controller, etc.) They begin this process by using general blocks, and then they gradually replace them with more specific representations (i.e. transfer functions). Figure 4 shows a complete schematic of the hardware.

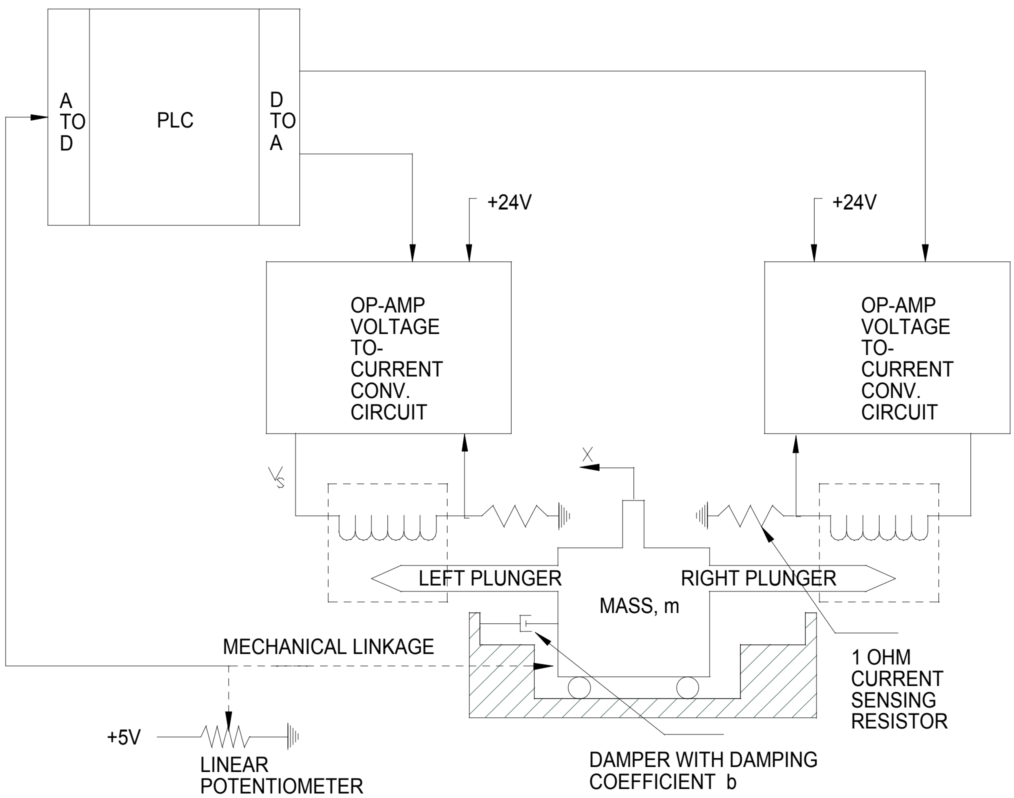
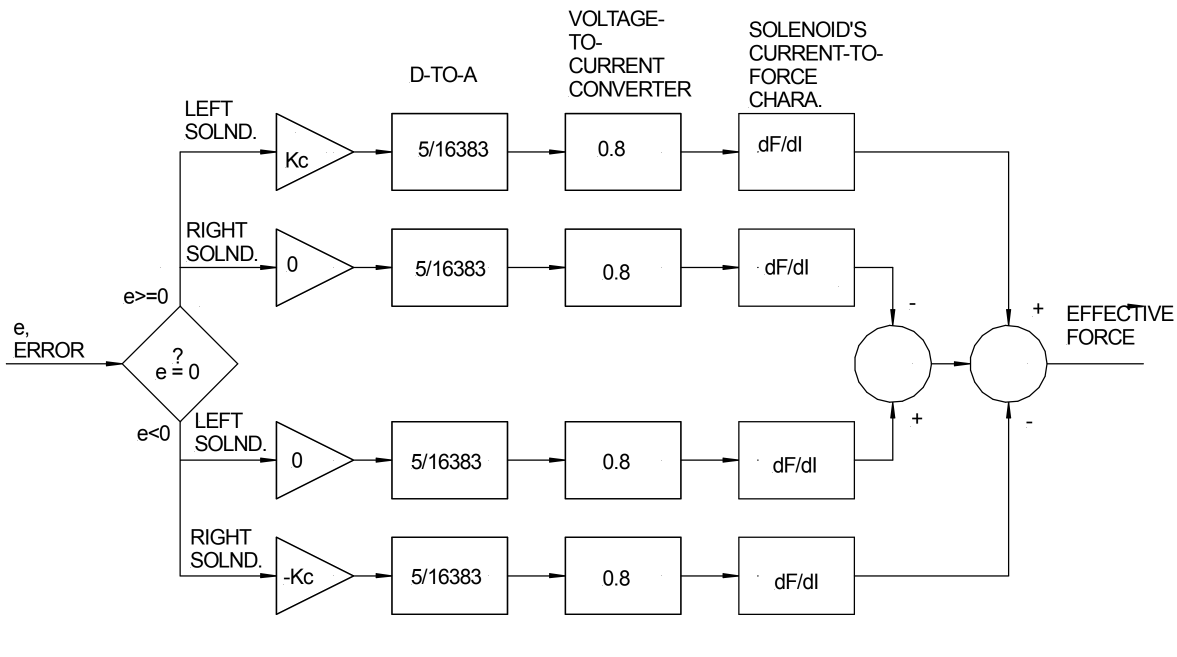
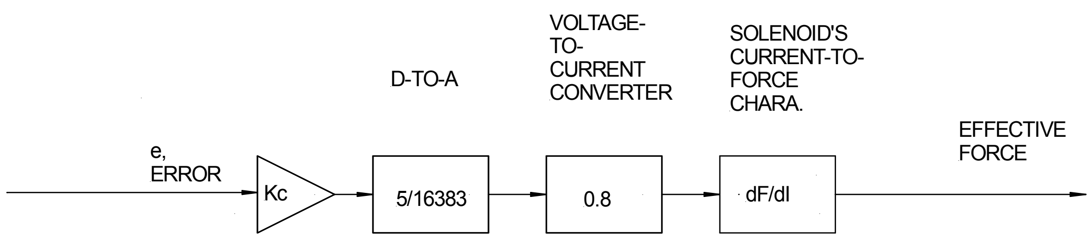


Figure 4: Complete schematic.

The fact that there are two solenoids but only one of them is active at any point in time is presented next. This is done by showing a block diagram representing all of the paths present, into a single path, as shown in Figure 5a and b.



(a) multiple path block diagram



(b) simplified block diagram

Figure 5: Simplification of multiple solenoids

Finally, through a series of student-to-student discussions and student group-to-faculty interactions, a complete block diagram is obtained. This is shown in Figure 6.

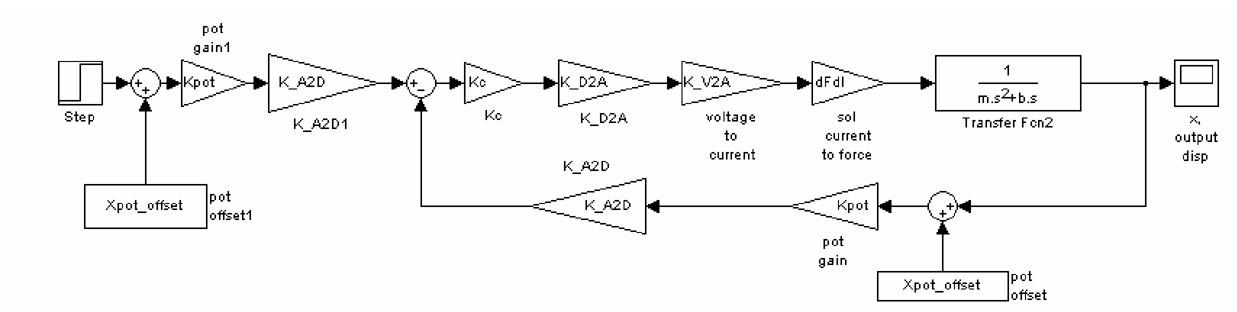


Figure 6: Overall block diagram.

Parameter Estimation

The next task is to ask them about the procedure that they would use in arriving at numerical values for the parameters. This assumes that they have access to all the physical components or relevant data books. This activity commonly takes place in a Socratic-style discussion, in which one student makes a suggestion and the rest of the students offer feedback and comments. Since, the amount of time is limited, at the conclusion of this discussion period; they are given most coefficients, to ensure that everyone has the same model. They are also informed, that some of the coefficients will be obtained at the moment that they work with the actual hardware.

Simulation

The next step is for the students to simulate the system using SIMULINK. The circuit is excited with a square wave in order to obtain a response similar to what will be experienced in the experimental phase. They observe that the when the controller's gain, Kc, is high, or the damping coefficient is low, the resulting transient response exhibits a significant Percent Overshoot (PO), as seen in Figure 7.

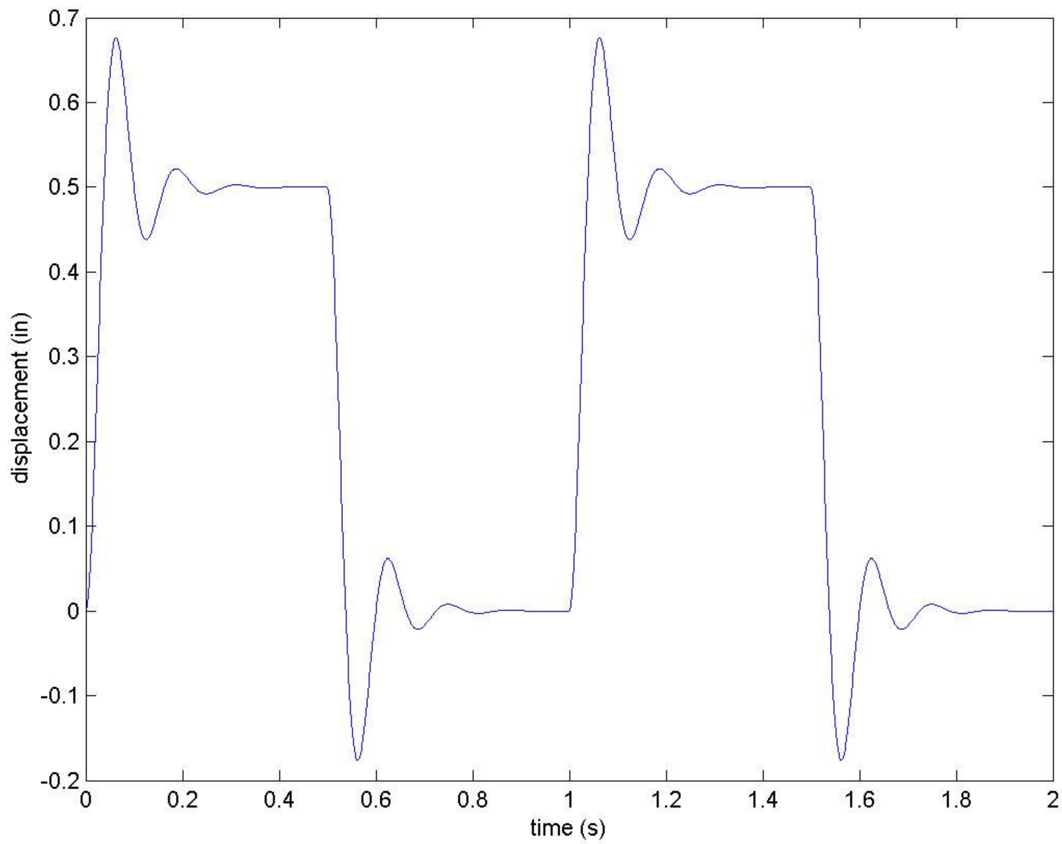


Figure 7. Simulation results.

PLC and Data Acquisition

In the first presentation, only a proportional feedback controller is used. In later experiments, the controller sophistication is increased until finally a full PID is used. One reasons for using the Allen-Bradley, MicroLogix 1500 LRP is that it has a built-in, data logging system, capable of storing up to 48Kbytes of data at very fast speeds. This PLC has two serial ports, one used for programming, the other port for retrieving data. This makes operation very easy, since no cables need be disconnected or connected during the entire operation. This assumes that the PC has at least two serial ports.

Experimental Results

Students then go to the laboratory where a real system has been set up. They apply the same excitation that was used in the simulation, namely a +/- 0.2in square wave command. They then compare the experimental results with the results obtained in the simulation. They also change the gain and observe the effect on the output. They observe the response in a storage oscilloscope, and when they have a response that is acceptable, they capture the response using the PLC's built-in, data acquisition system. Then they compare it with the results predicted by the simulation. Such an example is shown in Figure 8.

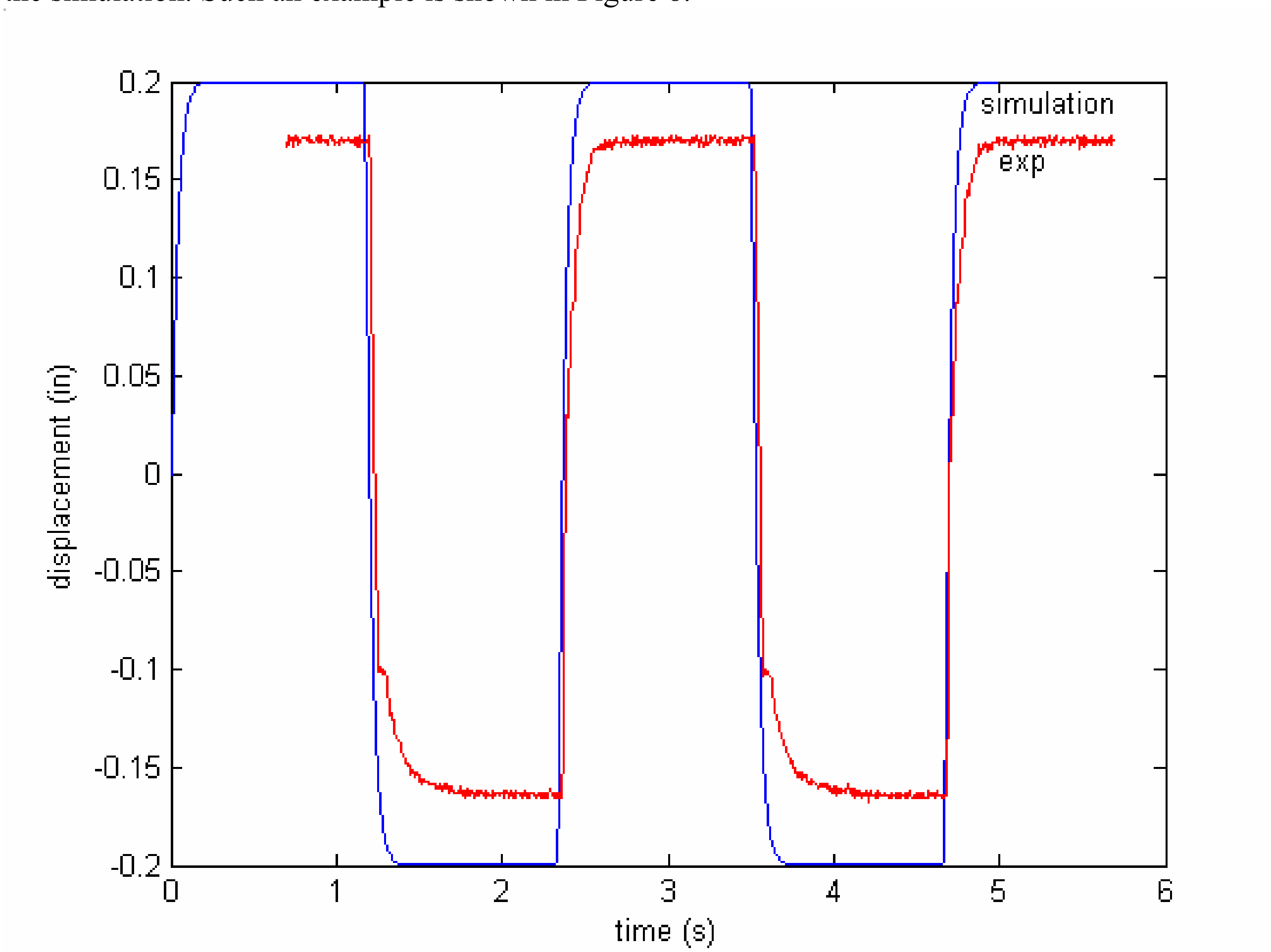


Figure 8: Comparison between simulated and experimental data.

Discussion

The students compare the simulated data and the experimental response. They expected zero-error after the transients die out, since the system is type 1. However, the experimental data reveals a steady-state error (see Figure 8). They are given the assignment of investigating why there is a difference. Eventually, they conclude that the Coulomb friction present in the system produces a steady-state error that is not predicted by the model used in the simulation.

Conclusion

This laboratory activity has been successful in reinforcing the concepts presented in the lecture. The students recognize the usefulness of modeling, parameter estimation, simulation, instrumentation and data acquisition. They also experience first-hand, the behavior of an almost-unstable control application. It has also been used as a spring board to other projects and applied research efforts, such as the incorporation of a Field-Programmable Gate Array (FPGA) to close the control loop [6]. Here the PLC only has to send the command signal to the FPGA, and is thus relieved from the task of actually closing the loop.

Acknowledgments

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