AC 2008-775: A METHOD TO UTILIZE A TISSUE ENGINEERING LABORATORY IN A CONTROL THEORY COURSE

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A METHOD TO UTILIZE A TISSUE ENGINEERING LABORATORY IN A CONTROL THEORY COURSE

Abstract

A carefully planned control theory course is capable of tying together many topics encountered in an undergraduate engineering curriculum. Some challenges are presented though when teaching such a course. Traditional control courses tend to be highly conceptual and include topics difficult for students to grasp[1]. To show students the real-world relevance of mathematical modeling and control theory, a biomedical research experimental laboratory was introduced into the course. Students were required to design a control system to operate a peristaltic pump for nutrient supply and waste removal to grow tissue for an actual research experiment. The introduction of an interdisciplinary laboratory exposed the students to the "big picture" of controls systems in a nontraditional setting. The project reinforced what was taught in lecture regarding PID type controllers and aided in understanding controls as they relate to actual systems. Students indicated that the laboratory improved their understanding of the concepts covered in class and homework. The primary reported benefit was an increased clarity between the relationships of the gains of a PID controller and their corresponding physical results.

Introduction

A control theory course tends to be a less tangible subject in engineering and thus was chosen as an ideal course to incorporate a laboratory to reinforce the theory[2]. Important information and transitional concepts are difficult to convey without practical application[3]. All too often students become frustrated by the bewildering task of trying to determine the real world relevance of the course. Typically, course curriculum is taught straight from a textbook like Ogata[4] or Franklin et al[5]. Students memorize formulas, recognize patterns and regurgitate information during tests. Our primary objective was to inspire students to *understand* control theory by developing a laboratory experience for the course. Other objectives for incorporating the bioengineering laboratory into a controls course were to:

1) Describe how changing P, I, and D control gains will affect the step response of a second-order system.
2) Design a proportional, integral, and derivative (PID) controller via a root locus plot, Bode diagram and tuning rules.
3) Physically implement a proportional, integral, and derivative (PID) controller.

Granted, there are many laboratories that reinforce control theory. Some curriculums involve using canned experiments like an inverted pendulum, controlling the rotation of a wheel, etc[6]. While all these experiments are admirable and augment the lecture well, the model employed in this laboratory was different. This laboratory was designed to solve a true life problem encountered at a large state funded university. Specifically, the laboratory was designed to create a method of controlling a cutting edge tissue engineering experiment that is ongoing in the department of chemical engineering. Different aspects of the experimental setup would be used in subsequent years to continually update the laboratory experiment while simultaneously solving an open research problem.

The laboratory consisted of a perfusion bioreactor for growing tissue. The controlling portion of the laboratory for this particular year utilized an AC servomotor and peristaltic pump head to circulate nutrient rich media through a scaffold. Students were responsible for characterizing the pump/motor system by using data collected from a real time board supplied by dSPACE[7]. By utilizing the theoretical concepts from lecture and the experimental data from the laboratory, students were able to obtain a mathematical model of the system. With this mathematical model, students then designed the controller type and optimized the gains within MATLAB[8]. After the controller was developed with the theoretical model, students downloaded the controller back into the dSPACE board to see how well it controlled the pump motor. In addition to the control experiment itself, some students were responsible to create a user's manual on how to use the control system which included a technical appendix on how the controller was optimized. This document would help future students either in biology or engineering build upon prior students works to further advance the laboratory. This paper will introduce the implementation of this project using the newly created tissue engineering lab.

The equipment:

The major components of the laboratory consisted of an autoclave to sterilize all of the required equipment, a laminar flow hood to provide a sterile environment to assemble the reactor, an incubator to control temperature, humidity, carbon dioxide percentage of the bioreactor, and a perfusion bioreactor to actually grow the tissue as shown in Figure 1. For this particular laboratory, the students focused on controlling flow through the bioreactor using a peristaltic pump-head driven by an AC servomotor. The pump system is used for circulating nutrient media through the bioreactor system to both seed a scaffold in the bioreactor as well as feed the cells.

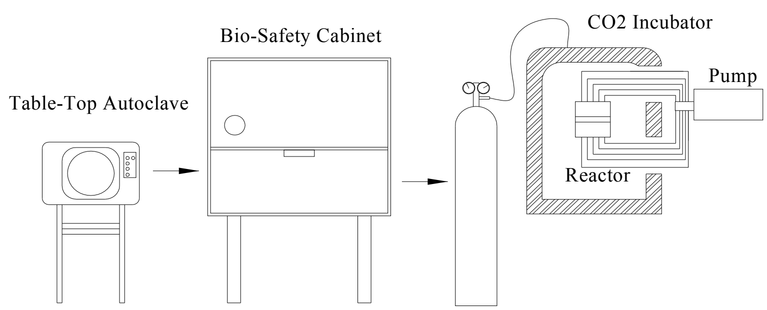

Figure 1. Overview of major equipment and setup.

The peristaltic pump system contains a motor (with optical encoder), gearbox, and an eight channel roller pump-head. The motor provides the necessary motion to the rollers which then depress the tubing to create the positive displacement of the fluid. The encoders provide the necessary feedback to the system. The 50:1 gearbox was included to decrease the speed of the motor as relatively small displacements of fluid were actually demanded by the pump-head. All components were assembled and aligned axially on a custom designed fixture shown in Figure 2.

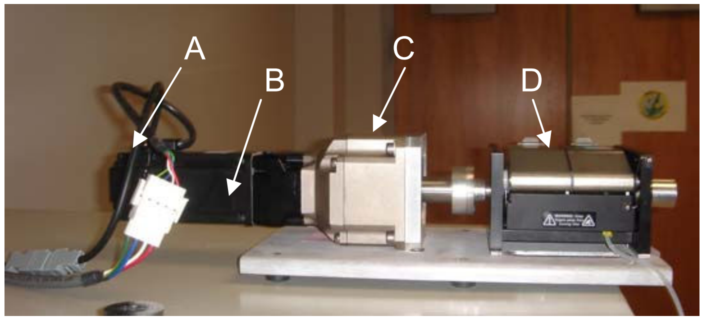

Figure 2. Completed pump assembly consisting of a A) Encoder, B) Servo motor, C) Gear head, and D) Pump-head

Control of the pump system motor (a Yaskawa SGMAH-04AAN21) was accomplished by using a dSPACE 1104 board interfacing with MATLAB on a computer as shown in Figure 3. The dSPACE board provided the necessary input voltage through its connector box which then was connected to a Yaskawa Servopack SGDH-04FE driver. The driver was programmed for torque control to override the built in controller. To create the necessary logic voltage signals (overtravel overrides, alarm reset, etc.) to the driver/controller, a switchbox was added and combined with a breakout board from the driver/controller. Control of the motor was performed directly with block diagrams in MATLAB Simulink. The combination of hardware and software allowed for students to simultaneously obtain real time data experimentally as well as full low level control of the motor by using simple block diagrams.

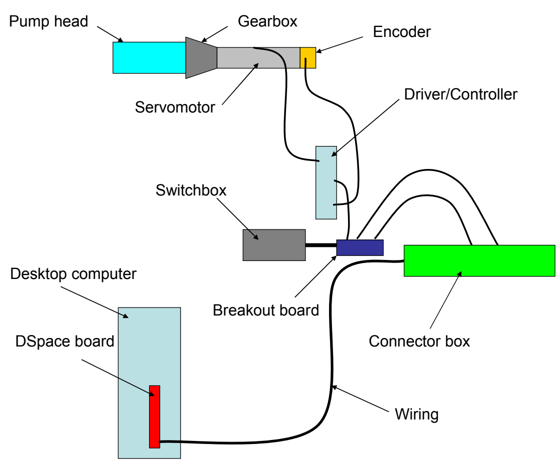

Figure 3. Peristaltic pump and associated control system..

In order to save on time on connections and preliminary debugging, the wiring and setup was completed prior to the students using the system. A simple control system was designed and given to the students so that the dSPACE specific Simulink blocks would not be a stumbling block to understanding of the system. A simple GUI was designed in ControlDesk (the real time interface to the dSPACE 1104 board) to provide graphical output of the system's performance.

Using the Laboratory as a Course Project

With about three weeks remaining in the control course, an experimental project was assigned involving the motor/pump system and control equipment. The class was divided up into groups of three to four students consisting of both graduate and undergraduates in each group. Groups were assigned arbitrarily although at least one graduate student was ensured to be in each group.

The groups were purposefully given minimal direction other than the requirements of the system along with a high level project overview. The lab environment was intentionally setup to mimic an industrial environment. They were shown the equipment along with the manufacturer's manuals and asked to make it work together. The instructor stayed out of the lab whenever possible to further allow the students to find the answer on their own. The instructor himself did not optimize the controller, thus allowing the students to solve the problem on their own.

The instructor divided the work requirements by seniority. The graduate student in each group was responsible with the aid of the undergraduates for creating a control system for the pump assembly. The undergraduates took the lead on creating the users' manual with the assistance of the graduate student. The users' manual needed to explain the overall control system in addition to how one would go about modifying it as well to suit their needs. Each group was then encouraged to, "work together."

The students were required to find a linear time invariant model of the system in order to design the appropriate controller and find the required gains. As there was no literature on the full system, the transfer function had to be obtained experimentally. However, the instructor provided a basic GUI in the ControlDesk program which interfaced with the system in real time. Students could then collect real time running data upon which to run experiments to determine the appropriate model. This same GUI also contained fields which could change the controller gains in real time so that different controllers could quickly be attempted.

Most students used an experimental approach introduced in lecture and homework called logarithmic decrement to obtain the damping ratio and natural frequency of the system. A step response in the form of a voltage was applied to the motor and the oscillation was recorded as shown in Figure 4. This allowed for the students to obtain an overall transfer function for the pump system that would incorporate all physical constants of the system.

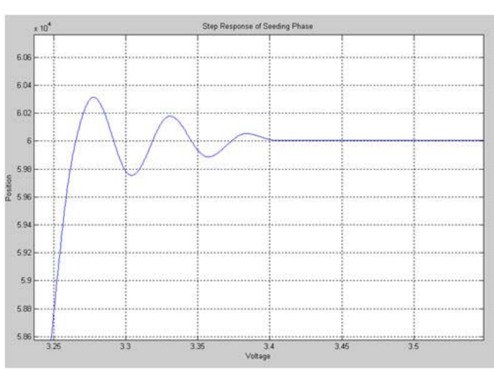

Figure 4. Graphical experimental data from step response into pump assembly motor.

Having a model of the transfer function of the system (plant) allowed for evaluation of different controller types (P, PD, and PID) offline within MATLAB. Many evaluated the modeled system using SISO Tool within Simulink and utilized a root locus approach to design the controller. SISO Tool also provided the option to have automatic tuning to obtain the gains for each parameter.

At this point many students had successfully characterized the system, designed an appropriate controller, and determined the applicable gains. When it came time for them to create a feedback control loop in MATLAB, many had questions on where to place the transfer function they had created. Much emphasis had been placed on developing an appropriate mathematical model within the class and homework that students lost sight of its purpose (i.e., it is a substitute for the real pump system for analysis purposes). The instructor had ran an in class example earlier in the semester showing this exact relationship but the concept was not fully realized until students were placed in the situation to manipulate both the mathematical model and the physical system it represented. Thus, many students asked for assistance and subsequently were able to make the connection (Figure 5).

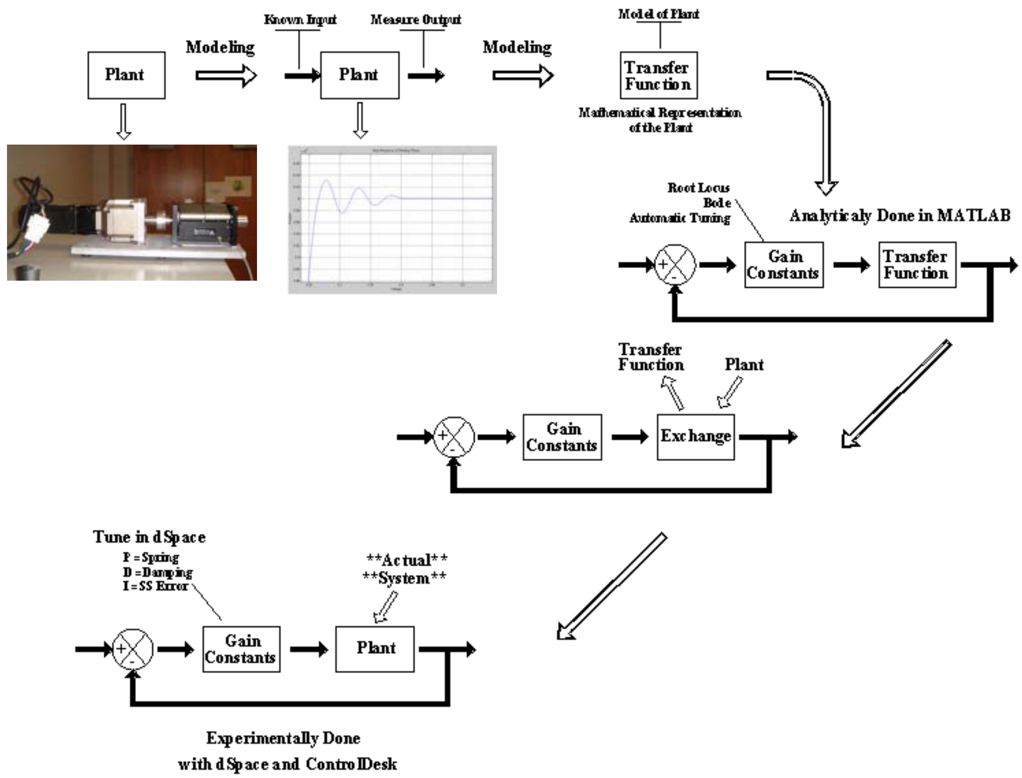

Figure 5. Overview of the system design focusing on the replacement of the transfer function for the actual plant system.

In the end, every group was able to design a controller for the system, to varying degrees, successfully controlled the motor in both position (seeding) and velocity (feeding). A large majority of the controllers were very good at following a prescribed position motion profile while a smaller number were able to fully satisfy a prescribed velocity profile. The users' manuals were impressive from the aspect of the detail and thought that went into completing the manual.

Assessment

The effectiveness of the laboratory was assessed by pre and post student surveys and an end of the semester focus group. Unfortunately, poor response on the post surveys due to the timing of giving the survey resulted in inconclusive data. The focus group, however, produced interesting results.

The focus group was conducted by a professor not associated with the course in which the students were asked the following questions:

1. What are the undergrads learning to do?
2. Is this related to what we are learning in class?
3. What is the relation between the class and project?
4. How did the project get started?
5. Was the project a positive experience?
6. Did you feel constrained with the requirements?
7. Does it matter what the system you are trying to control is?
8. Do you recommend this project and laboratory be done in the future?

Overall, students were pleased with the integration of a controls project into the bioengineering laboratory. They appreciated being able to apply lessons learned in class to an experimental setup outside of their expertise. Many statements were made during a post interview about how much they learned during this segment of the curriculum. Ultimately, the students realized the connection between the mathematical concepts taught in class and how they physically relate to a control system.

For example, a typical response to the question "What is the relation between the class and project?" was "This has been one of the first projects that really related what the class is about to a real life example. I mean sometimes we learn different topics that we don't use or only in the senior year. It is really nice to apply something learned a few classes ago to something that is very much real world." Another student responded, "It becomes really clear what happens between theory and experiment." Another student responded, "It's cool to see how the actual math works because before I would hit a button and something would happen and not know why. But now I actually understand the math behind it and a little bit of the theory to show why when I change this number it does what it does." Another series of responses to the question, "How did the project get started," and "Was the project a positive experience," were, "The professor threw us into the project and said 'I expect questions. Go down to the lab and see what you can do', This is kind of what happens in the real world." "This was a positive thing because it forced you (the students) to get hands on and play around with the system." "We would work with the system, come up with some questions and go to Dr. Voglewede, and he would make it clearer."

Remarks

Presenting the fundamentals of control theory can be challenging. Introducing concepts in conjunction with real world examples helped students understand control theory better. Furthermore, during the project, students made invaluable connections between mathematical theory and physical behavior.

Initially, students were anxious from the freedom and minimal direction given within the lab. However, they quickly rose to the challenge of assuming a proactive role in asking questions, which led to improved understanding of the topic. The students recognized the relevance of the real world application and gained a greater appreciation of control theory. The expression of the students was one of excitement, the moment they realized they themselves had designed a control system from scratch with minimal assistance.

The laboratory in the future will incorporate other aspects of control for the bioreactor system. Specifically, the pH of the fluid is targeted next as it directly affects the growth of the tissue. Thus, the opportunities for continually updating the laboratory while simultaneously aiding in the research objectives of the experiment are numerous. This experiment will also be utilized in other courses with an emphasis on the integrating concepts together for students.

Since the students' reaction to the lab and project was a positive one, it seems most appropriate to recommend this method to other teaching establishments. However, several challenges exist for initiating a laboratory and program like the one presented above. One challenge for the professor will be to judge how much instruction students will need. Thus, an open environment must be fostered during the entire course to enable the instructor to have the feedback necessary to interject appropriate instruction to the student. A second challenge is the capital investment in the project is large as bioengineering experiments are costly. Third, it requires buy-in from all the professors involved. Nevertheless, this laboratory experience ultimately created the connection between the theory and physical world.

Acknowledgement

This work was supported by a National Science Foundation Course Curriculum and Lab Improvement award (DUE-0633648). All opinions expressed within are the authors' and do not necessarily reflect those of the National Science Foundation.

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