A MODULAR DESIGN FOR

AN UNDERGRADUATE SYSTEM DYNAMICS AND CONTROLS

LABORATORY

by

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B.S., Mechanical Engineering
University of California, Los Angeles, June 1993

Submitted to the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

MASTERS of SCIENCE
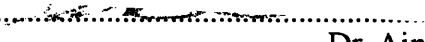## in MECHANICAL ENGINEERING

at the

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ABSTRACT

The broad applications of control engineering have created a need for hands-on laboratory experience in system dynamics and controls in the undergraduate mechanical engineering curriculum. At MIT, the core course, Principles of Control, includes a significant laboratory component. However, due to the heavy usage of over 160 students per year, and the lack of modernization over the past ten years, this laboratory does not fulfill its potential as one of the key educational experiences in the Mechanical Engineering curriculum. The equipment relies on decade-old technology, and suffers from severe wear and tear. To correct this situation, a prototype laboratory that will meet the educational needs of MIT undergraduates for the next decade has been developed.

The prototype laboratory has the following advantages:
- The laboratory exposes students to state-of-the-art equipment and techniques, such as working with a digital computer on real-time control systems.
- The laboratory has a modular structure which allows for expansion over time, future integration of new technologies, and incorporation into the curriculum of other classes.
- To reflect the interdisciplinary nature of controls engineering, the laboratory includes two physical plants representing two disciplines of Mechanical Engineering (Electromechanics and Fluids).
- The laboratory has a connection to the MIT campus-wide computer network, ATHENA, allowing the students to preview laboratory materials, access supporting information, perform simulations, and interact with the laboratory instructors on-line, prior to the laboratory.

Thesis Supervisor: Dr. Steven Dubowsky
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ACKNOWLEDGMENTS

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CHAPTER 1

INTRODUCTION

1.1 Background & Motivation

The Massachusetts Institute of Technology's Department of Mechanical Engineering has a three course sequence of undergraduate classes in systems dynamics and controls. Two courses cover modeling and dynamics (course # 2.02, 2.03J). They provide no laboratory experience for the students (Appendix A). The third course, Principles of Control (course # 2.14), includes a significant laboratory component. This course is an introduction to classical control system principles and their practical applications. Over the past 10 years, an average of 160 students per year have registered for this course. The course is generally taken by juniors and seniors from the Mechanical Engineering Department, although a handful of sophomores and graduate students also take the class. Moreover, the course also draws from departments across the Institute, including Electrical Engineering, Ocean Engineering, Civil Engineering, The Sloan School of Management, and the Division of Applied Sciences at Harvard. With a mechanical engineering undergraduate class size of 125 students, this means that most mechanical engineering undergraduate take 2.14 with its laboratory even though it is not a required mechanical engineering course (refer to Appendix B for detailed course enrollment). Due to its popularity and core educational content, 2.14 with its laboratory is an essential component of MIT's mechanical engineering curriculum.

Even though the current Control Systems Laboratory continues to be used in the 2.14 course, both the faculty and the students have expressed the need for substantial laboratory improvement. For the past ten years, the laboratory has seen little upgrading or modernization. As a result, the technology in the laboratory is quite dated. For example, the students "build" their control systems by "patching" analog computers. This technology dates from the 1960's and 1970's. Moreover, the equipment is aging and unreliable. The students and laboratory instructors spend too much time dealing with the equipment problems rather than performing educationally meaningful experiments. As a consequence, the educational value of the laboratory is seriously compromised, which

might explain the steady decline in class enrollment (Appendix B).

To give a better perspective of why the laboratory needs to be improved, a description of the current laboratory follows. The laboratory is equipped with five relatively simple rotary servo experimental set-ups which accommodate a maximum of 15 students at a time. Each set-up consists of a servo amplifier driving a DC torque motor with an attached rotary inertial load. An analog computer (Comdyna GP-6) is used to implement controllers and perform analog simulations. An oscilloscope is used as a measuring device, and a function generator is used to generate sinusoidal inputs. System input is a voltage to the amplifier, and the measured outputs of the system are the angular speed or position sensed by a tachometer or a potentiometer respectively. Figure 1.1 shows the current system.
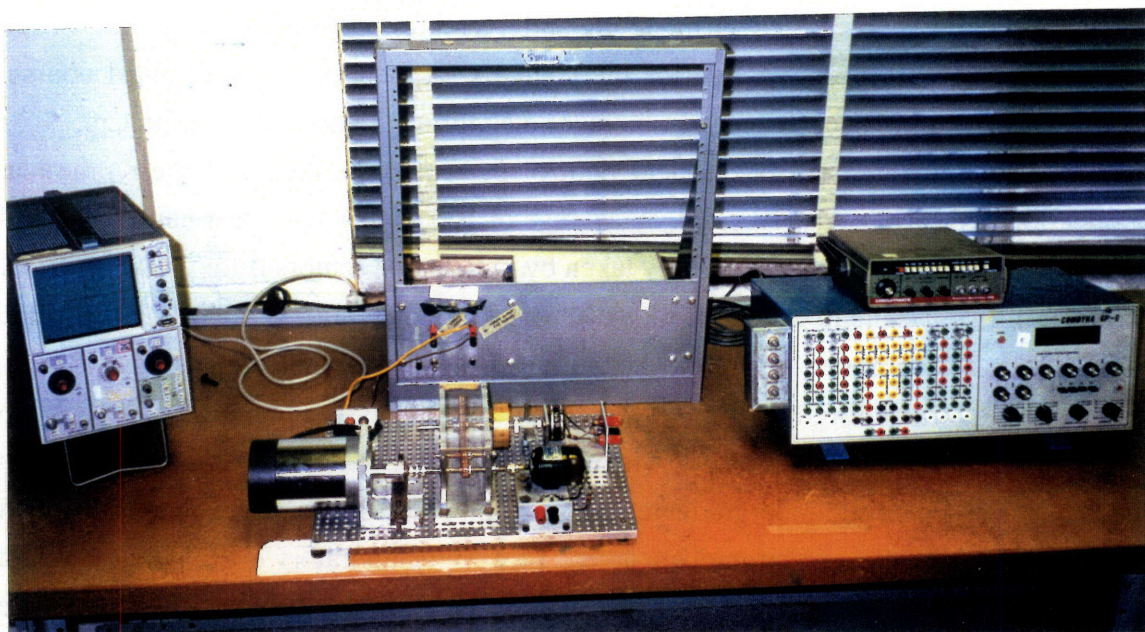
Figure 1.1: Workstation Layout in the Control Systems Laboratory
From left to right, shown are: the Analog Oscilloscope, the Plant (Belt Drive System with DC Motor, Tachometer, and Potentiometer), the Servo Amplifier, the Comdyna, and the Function Generator located on top of the Comdyna.

Because the students can only control the angular velocity and/or position of the inertial load using analog computers, the range of simulations and design studies they can perform in the laboratory is limited. Also, the system is not expandable. Additional components cannot easily be added to illustrate dynamics of different types of physical systems, or more advanced control concepts. As a result, the students are currently exposed to only one field of mechanical engineering (electromechanical systems). Applications of control principles to thermal or fluids systems are not treated. This

provides the students with a very narrow view of dynamics and control. Moreover, with the current non-modular environment, the laboratory equipment is dedicated solely to the needs of 2.14 and cannot accommodate other classes which could benefit from hands-on experience in dynamics and control. Furthermore, the laboratory does not exploit the use of MIT's campus-wide computer network, ATHENA. With its old-fashioned use of Xerox laboratory handouts, pencil and paper data acquisition and analysis, the report writing is inefficient in terms of the instructors' and students' time. In addition, the large enrollment of the class, along with the relatively small number of working stations, requires three students to work together on one station.

The equipment of the current Control Systems Laboratory is old and unreliable, the technology is obsolete, and, most importantly from an educational point of view, the system does not interest or challenge students. These limitations have motivated the Mechanical Engineering Department at MIT to sponsor the development of a prototype System Dynamics and Controls Laboratory with radically improved equipment, methodology, and intellectual content. This research project, started in Fall 1993 and supervised by Professor Steven Dubowsky, was carried out by two master's students, Richard Wang and myself. We were joined in Fall 1994 by two undergraduate students, Jason Hintersteiner and German Soto. The goal of this project is to meet the current needs of MIT, anticipate and facilitate the implementation of its future needs, and provide a model for other schools facing similar laboratory renovations.

1.2 Overview

The most important issue in creating the new System Dynamics and Controls Laboratory is to ensure a successful and efficient interaction between the students and the experimental set-ups. To achieve this, choices must be made on three different levels, educational, design, and technical, with the design bridging the gap between the educational and technical levels.

For example, on the educational level, the prototype system should permit students to experience control principles on experimental set-ups illustrating different fields of mechanical engineering. Therefore, on the design level, it was decided that the prototype system would be modular, and have an open architecture. To implement these design objectives on the technical level, the prototype system is to include three modules (computer, electronics, and physical), two physical set-ups (a water level control system, and a linear slide table), and allow room for a challenging design project (Figure 1.2).
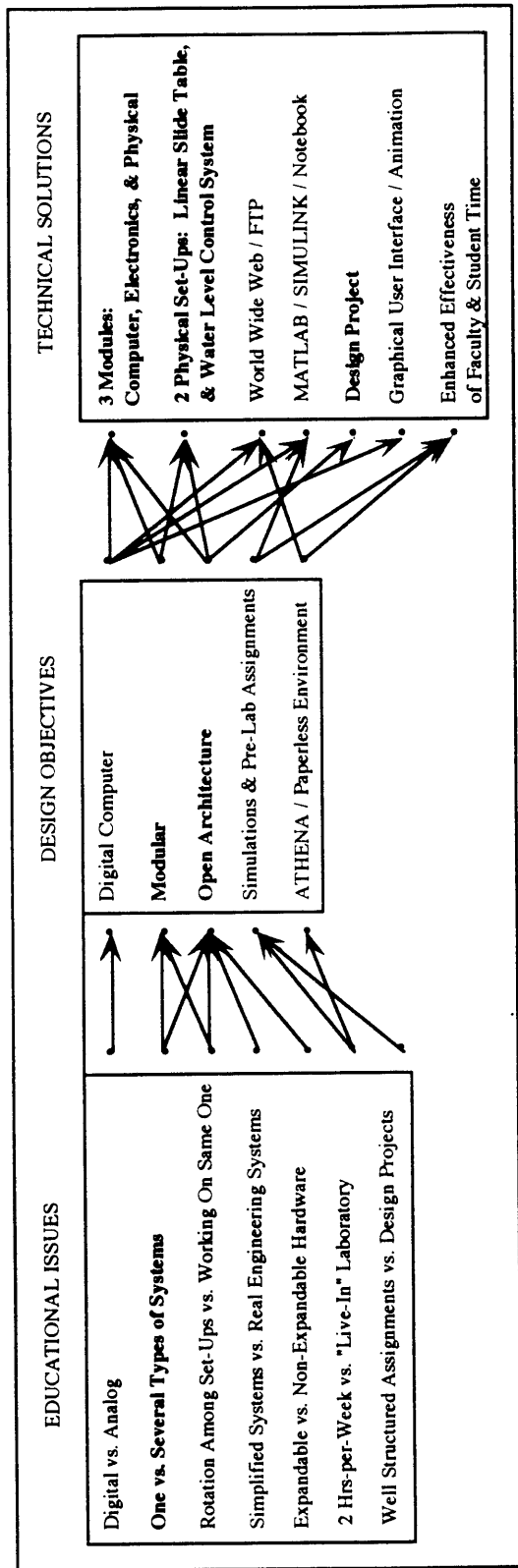
Figure 1.2: Decision Process on Three Levels

Figure 1.2 gives an overview of the scope of the project, indicating the connections between the different levels and showing the range of interrelated choices we had to make while developing the new laboratory.

1.3 Contribution

This thesis is part of a collaborative effort by a team of four people. It mainly focuses on the design and development of the electronics module and the water level control system, one of the two physical set-ups. This thesis also details the new laboratory environment including the workstation layout and laboratory floor plan.

Richard Wang's thesis [48] concentrates on the development of the real-time control software building blocks, the graphical user interface, and the overall structure of the software. It also details the design of the linear slide table, the other physical set-up.

Jason Hintersteiner's thesis [19] focuses on the network interface between the laboratory computers and ATHENA, the MIT campus-wide computer network. This thesis also covers the structure of the real-time control software.

German Soto's thesis [45] details the design and fabrication of the water level control system.

1.4 Thesis Outline

The discussion in Chapters 2 through 8 of this thesis follows the three level structure of Figure 1.2, systematically presenting the educational issues faced, and detailing the decisions made on both the design and technical levels.

Chapter 2 links the educational and design levels by identifying the educational issues raised by the MIT controls faculty in the Mechanical Engineering Department, by reviewing the solutions chosen at other universities facing a similar renovation process, and by laying out the major design decisions.

Chapter 3 links the design to the technical level by presenting the overall design concept and its implementation through the use of three modules: computer, electronics, and physical. It goes over the choice of two physical set-ups, the teaching method, the link to ATHENA (the MIT campus-wide computer network), the enhanced effectiveness of the faculty and student time, and finally the laboratory environment.

Chapter 4 focuses on the computer module. It describes the equipment contained in that module, and gives an overview of the software written for the real-time control, the graphical user interface, and the computer animation. The interface between MATLAB (used for data analysis) and Microsoft Word (used in report write-ups) is presented and evaluated. Chapter 4 ends with a discussion on the World Wide Web used

for viewing the laboratory material.

Chapter 5 focuses on the electronics module. It presents the major components' function, and their selection process. The design criteria for the electronics module, and their implementation, are detailed. The interaction between the electronics module and the other two modules is described. The upgradability of this module is discussed. Chapter 5 ends with a cost breakdown of the electronics module.

Chapter 6 focuses on the fluids module, which is one of the two physical modules. It goes over the choice of the preliminary design and its feasibility analysis. The selection of equipment and material is discussed. The steps to ensure compatibility between the computer, the electronics, and the physical modules are detailed. Then, the discrepancies between the simulation and experimental results are covered. Finally, the design is evaluated, and the necessary maintenance procedures are listed.

Chapter 7 is an evaluation of the work done using feedback from current 2.14 students. It covers the preparatory work done, the profile of the students recruited, and the test method. It also presents the results of the student testing.

Finally this thesis ends with some concluding remarks in Chapter 8.

CHAPTER 2

FROM EDUCATION TO DESIGN

2.1 Educational Issues

Before any designs were considered, an understanding was sought of what the mechanical engineering faculty was looking for in an undergraduate System Dynamics and Controls Laboratory. Issues related to the intellectual requirements for the laboratory were investigated through faculty interviews. The goal was to gather information about which principal concepts the new laboratory should present, as well as how those concepts should be illustrated through various experiments. A total of 17 MIT Mechanical Engineering controls faculty members were interviewed by the two graduate students of the team. Moreover, since the topic of systems dynamics and controls is not taught exclusively in the Mechanical Engineering Department, professors from other departments (Electrical Engineering, Ocean Engineering, Aeronautics and Astronautics) were contacted, though only one professor, from the Ocean Engineering department, contributed significantly. Our objective was to learn how other departments approach the subject and teach it to their students. As a further input to our research, professors from other universities were contacted. The list of MIT and non-MIT faculty consulted is included in Appendix C.

As a result of this extensive interview process, the following key intellectual concepts were deemed important to embody in the prototype laboratory:

- Modeling / System Identification

  examples: equations of motion, Laplace transforms, transfer functions.
- Simulation Methodology

  example: block diagram representation.
- Dynamic Behaviors

  examples: plant parameters variations, external disturbances, friction.
- Feedback and Control

  examples: open loop vs. closed loop control, first order and second order system response, proportional, derivative and integral control.

- Controller Design

    examples: root locus, Bode plot, Nyquist, Routh-Hurwitz, lead/lag compensators.
- Introduction to Discrete Time

    example: sampling frequency variations.
- Advanced Topics in Controls

    examples: MIMO systems, nonlinear control, stochastic control, optimal control,

    adaptive control.

It was clear from the faculty response that the goal of this laboratory is not to introduce these concepts to the student, but to provide the hands-on experience essential for a deep understanding of these concepts, which can only be achieved by the interaction between the student and a real physical system.

During those interviews, a wide range of educational issues, primarily related to the physical hardware and the computer interface, were raised by the various faculty members. A summary of those issues and a discussion of their educational value follows.

Digital vs. Analog:

The use of digital equipment assists the teaching process in several ways. Though simulations can be performed on both analog and digital computers, only the digital computer allows for direct comparison between the simulated results and the experimental results due to the analysis capability gained from using programs such as MATLAB from The MathWorks Inc. Moreover, a digital computer yields higher quality results. Finally, it saves time for both the teaching staff and the students by significantly reducing, if not eliminating, the time spent debugging the equipment. Typically, students spend approximately half of their time in the laboratory "patching" the analog computer. However, since 2.14 focuses on control concepts in the continuous time domain, to avoid confusion, students should not be introduced to digital control in the laboratory. Some faculty members supported the use of an analog computer to provide experience in building operational amplifier (op-amp) circuits. Op-amp circuits expose the students to the building blocks of lead and lag compensators, currently not covered in the laboratory. However, others argued that learning op-amp circuit building is an unnecessary overhead for learning fundamental control theory.

One vs. Several Types of Systems:

Exposing students in the laboratory to only the electromechanical domain limits their understanding of the vast applications of controls concepts. Therefore, a prototype with a number of different set-ups which would illustrate other domains of mechanical

engineering was suggested. Having this versatility permits other classes to take advantage of the laboratory as well, and therefore produce a more integrated mechanical engineering undergraduate curriculum. With the prospective of the mechanical engineering undergraduate curriculum being changed, and the uncertain fate of 2.14, this versatility carries even more weight. The use of the prototype System Dynamics and Controls Laboratory needs to be expanded to classes other than 2.14. Some professors did argue, however, that too many different types of systems will lead students to spend too much time worrying about the specifics that change from one plant to the other rather than the fundamental principles common to all plants.

Rotation Among the Various Set-Ups vs. Working on the Same Set-Up:

A new teaching philosophy, which involves having each group of students work on a different physical set-up every week, was judged worthwhile because it introduces students to a greater number of systems. Doing so exposes the students to a variety of sensors, as well as systems and control applications from different mechanical engineering domains; however, it prevents the students from becoming thoroughly familiar with any one set-up since they will not be given extensive time exposure on any one of them.

Simplified Systems vs. Real Engineering Systems:

Several faculty members complained about the lack of in-class demonstrations in 2.14. To resolve this problem they proposed building for the prototype laboratory several small, robust and reliable physical systems which could be brought to class. Since the purpose of those demonstrations is to illustrate specific theoretical concepts, the system response needs to be clean (i.e. free of obvious noise and friction effects). On the other hand, it was argued that real engineering examples should be used to allow students to build a bridge between the theoretical concepts and their real world applications. The advantage of doing so is to expose students to actual engineering products found in the industry, and therefore close the gap between theory and practice, school and industry. However, the added complication in actual engineering products may confuse the students, and make it harder for them to understand the underlying concepts.

Expandable vs. Non-Expandable Hardware:

Whether the system is a complex piece of industrial equipment or a simplified model of it, it was considered important by the interviewed faculty to keep the hardware expandable and therefore more flexible. Having this flexibility adds to the educational

value of the hardware. For example, students will be given the opportunity to study the dynamic behavior of the system by changing some plant parameters in a consistent manner, which is not possible in the existing undergraduate Control Systems Laboratory. Currently, when students are asked to exert a constant frictional torque on the system, they must do it with their hands; a procedure with very low repeatable results. One professor suggested that the hardware be built as a "lego-like" system. The disadvantage of expandable hardware, however, is that the system becomes less robust since there are more movable parts.

2 Hours-per-Week vs. "Live-In" Laboratory:

The amount of time each laboratory session should take needs to be determined in order to identify the format the laboratory sessions should have. The "live-in" type of laboratory requires the students to work approximately 8 hours per week in the laboratory. This will not only allow students to obtain more in-depth experience in controls, but also allow for more topics to be illustrated in the laboratory. Unfortunately, the additional time commitment for such a format would be excessive for the already heavy work load of the class. On the other hand, the 2 hours-per-week format requires the complexity of the experiments to be kept to a minimum. Related to the amount of time students should spend in the laboratory, two suggestions regarding laboratory assignments were proposed. Some professors favored having a different short assignment every week because it would take less time for the instructors and students to get familiar with the content of the assignment. Others, judged those short assignments as "canned" experiments, and preferred to see a few long assignments spread out over several weeks.

Well-Structured Laboratory Assignments vs. Design Project:

A project would, for example, present the students with a set of specifications, and, given several weeks, ask them to design the controller. The proponents of the design project idea view the project as a means for students to sum up and apply the concepts they have learned in class. On the other hand, the opponents claim that a design project will only end up as a written report with no applications to the physical hardware and thus will lose its educational validity.

Before identifying the link between the design decisions and the educational issues, I will review the directions being taken by other engineering schools facing similar situations while designing an educational controls laboratory.

2.2 Literature Review

Several common themes emerge from many reports describing implementations or renovations of laboratories to teach control theory. Whether this laboratory serves the Electrical Engineering Department, the Mechanical Engineering Department, or the Aeronautics and Astronautics Department, the instructors want to complete the students' education in control theory by giving them hands-on experience, and therefore the ability to understand what is done in industry. Furthermore, they agree that students should be given the opportunity to model the physical system first. The actual implementation of the laboratory varies depending on the school and the funds available.

Most schools have opted to build a laboratory using digital computers, with the appropriate software to perform data acquisition, data analysis, and simulations in conjunction with physical hardware. Thus, digital devices are used to control analog devices as is done in industry. Three schools, however, Ohio State University [49], University of Texas at San Antonio [37], and University of Washington [47], chose to expose their students to an analog component in the laboratory. Ohio State uses the Comdyna analog computer to replace the "real" physical plant. The premise is that any plant can be represented by op-amps, therefore the laboratory keeps its "generic" nature by replacing the physical plant by an analog circuit. Moreover, the author states that using analog circuits will emphasize fundamentals [49]. University of Texas at San Antonio uses the Comdyna GP-6 analog computer to simulate a plant transfer function, but also exposes the students to actual physical plants [37]. It is not clear to me why the authors chose this direction since, among the software purchased for the laboratory, there is MATLAB and SIMULINK from The MathWorks Inc. which can perform simulations of transfer functions. The developer of the new Control Systems Laboratory at the University of Washington declares that a few analog computers are used so that "students can gain some experience with more traditional control systems mechanization," but the laboratory mainly uses digital computers [47].

One common factor among all papers reviewed which listed the equipment in detail, is that the software used in the new laboratory is available commercially. Some of the commonly listed packages are: MATLAB/SIMULINK, LabVIEW, CC, Excel. On the other hand, the same trend was not found for the physical hardware. In most institutions, the plants students would be simulating and controlling were designed and built in-house. Only when the purpose of the laboratory was to control or automate typical manufacturing operations and industrial processes was the hardware commercially available [37]. I suspect this trend is due to instructors seeking a simple, robust, and

reliable system which would illustrate the fundamental control concepts clearly, while commercial products are often too complicated for educational purposes. Almost all papers describe experiments designed on electromechanical plants, and many ([1, 4, 5, 6, 8, 15, 21, 22, 23, 26, 27, 33, 39]) describe experiments illustrating control concepts on plants from other domains of mechanical engineering as well. Some experiments use fluids plants where the goal is to control the tank water level [1, 4, 6, 15, 21, 22, 27, 33, 39]. Though the control objective is the same in all cases, no two papers describe the same physical set-up. In some cases, the plant is composed of an AC powered pump, others a DC powered pump. The number of tanks vary from one to three, and their relative location is always different. Also, the valves connecting the tanks are either on/off valves or needle valves. Other experiments use thermal plants which vary from heating rods, to heat exchangers, to heating and ventilation systems [1, 5, 6, 8, 15, 23, 26, 39]. Within each category there are differences. For example, depending on the material used for the heating rod, the system response will be different.

In general, faculty members agreed that exposing students to more than one engineering domain would be advantageous to both the student and the school. On the one hand, the student would gain a better understanding of the theory, and with the increasingly interdisciplinary nature of engineering, the student's education will be more well rounded. On the other hand, the same laboratory could be used for several classes, therefore saving money for the school.

A few faculty members believe that the laboratory should introduce the students to control concepts beyond the ones covered in class [5, 22, 47]. Specifically, the laboratory should demonstrate to students the controller's limitations due to nonlinearities. For example, at the University of Washington, advanced control concepts are illustrated by allowing for new features, which require more advanced techniques for successful control, to be added to the existing hardware [47]. The possibility of altering the hardware calls for a flexible design.

Keeping the laboratory up-to-date, interesting and challenging to the students is an issue discussed in [6], [22], [27] and [47]. In all cases the faculty realized the need for a versatile laboratory which permits upgrades with minimal modifications as technology evolves. This upgrade can be done by using senior projects and master's theses to create new experiments, as in [27], or by using the laboratory to perform research activities, as in [47].

Another tool mentioned in the papers reviewed to facilitate the teaching and learning of control systems is computer animation programs [13, 21].

All of the issues mentioned in this section were raised, directly or indirectly, by

the controls faculty at MIT. In the next section, I correlate the educational issues with design decisions, present our prototype's unique features, and explain why certain issues were solved differently from previous efforts at other schools.

2.3 Design Objectives

This section lays out the most important design decisions.

The faculty overwhelmingly leaned towards the use of digital computers in the prototype laboratory. However, as pointed out in section 2.1, using digital computers has some limitations. 2.14 students will work on digital computers throughout the semester, but will not be introduced to digital control theory until the end of the semester. To resolve this discrepancy, it was decided that the digital aspect of the control loop should be masked. To satisfy the desire for analog control in the laboratory, the decision was made to include an analog loop in addition to the digital computer so that students can build lead and lag compensators. Chapter 5 explains how this analog loop is implemented.

To exemplify the versatility of the prototype laboratory developed by the team, two physical set-ups representing two different areas of mechanical engineering were included in the prototype. As will be discussed in later chapters, each set-up was designed to provide some flexibility so that plant parameters could be changed to study the dynamic behavior of the system. Including two different plants in the prototype called for a modular design approach to limit the changes needed in controlling different plants.

A modular approach also solves the problem of simplified systems vs. real engineering systems. Though the two set-ups are used to illustrate fundamental control theory, the hardware purchased for data acquisition was chosen to accommodate more complex systems. For the faculty members who want to use the laboratory equipment for in-class demonstrations, we have designed the set-ups to fit on a table top.

As an alternative to the two hours-per-week or "live-in" laboratory format, performing take-home pre-laboratory simulations was mentioned. The advantages of pre-laboratory simulations are to give students the opportunity to exercise their modeling skills, and become familiar with the experiment by predicting, from theory, the system response. Thus, by giving students a small pre-laboratory exercise we can contain the laboratory time to two hours-per-week, and still study some concepts in depth without sacrificing the breadth of concepts covered. Moreover, with the time saved by using digital computers, since debugging the equipment is no longer an issue, laboratory time is more efficiently focused on experimenting with control concepts.

For student convenience, and to allow for future development, we decided to put the materials for the new System Dynamics and Controls Laboratory on-line using the campus-wide computer network ATHENA. This connection allows students to perform all their pre-laboratory assignments from any ATHENA terminal, and view their results from the laboratory computers. This method also prevents students from "forgetting" to bring their homework to class, and minimizes the use of paper. ATHENA being unique to MIT, the network features mentioned in this section are the most unique features of our prototype compared with any other laboratory development discussed in the literature reviewed.

So, to integrate the various faculty suggestions on the physical hardware and computer interface, the renovated laboratory is designed to provide:

- Exposure to real-time digital control technology.
- An open architecture to permit upgrading and growth.
- Modular structure for integration of interdisciplinary modules.
- Robust hardware and software.
- Integration into ATHENA, the MIT campus-wide computer network.

Figure 2.1 integrates the design decisions presented in this section, and illustrates the interaction between students and the experimental set-up.

STUDENTS

Control Law Design
Simulations
Reference Command Input
Result Display

Modeling
Analysis
"Senses"
(See, Touch, etc.)

COMPUTER

ATHENA

Control Law Implementation
Data Measurements
Control Command Output

Rotational   Translational

Thermal /
Heat   Fluidic

PHYSICAL
HARDWARE
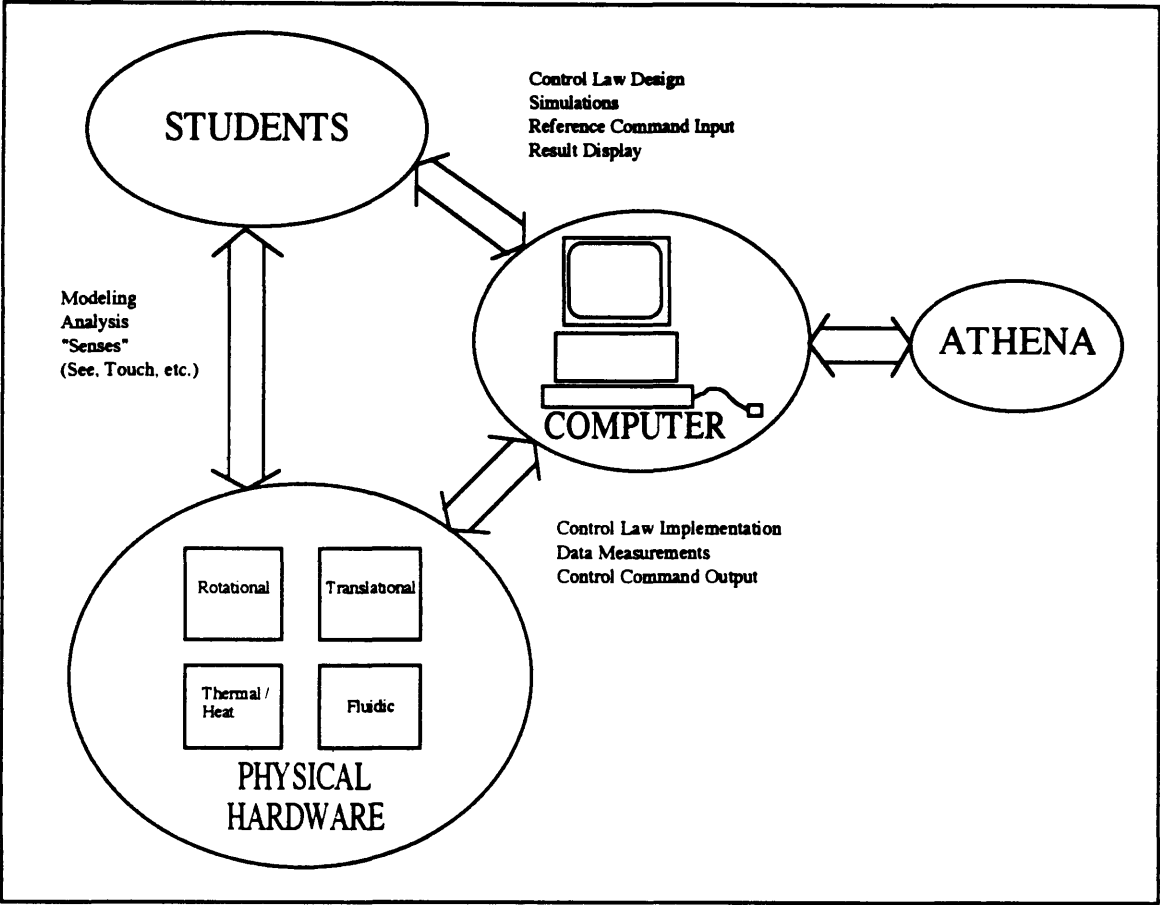
Figure 2.1: Proposed Interaction Between Students and Experimental Set-Ups

CHAPTER 3

OVERALL DESIGN CONCEPT

3.1 Three Modules

To provide for an open architecture, which is crucial for the laboratory's flexibility and its capability to evolve, each laboratory station was designed to include three modules: a computer module, an electronics module, and a physical module (Figure 3.1).
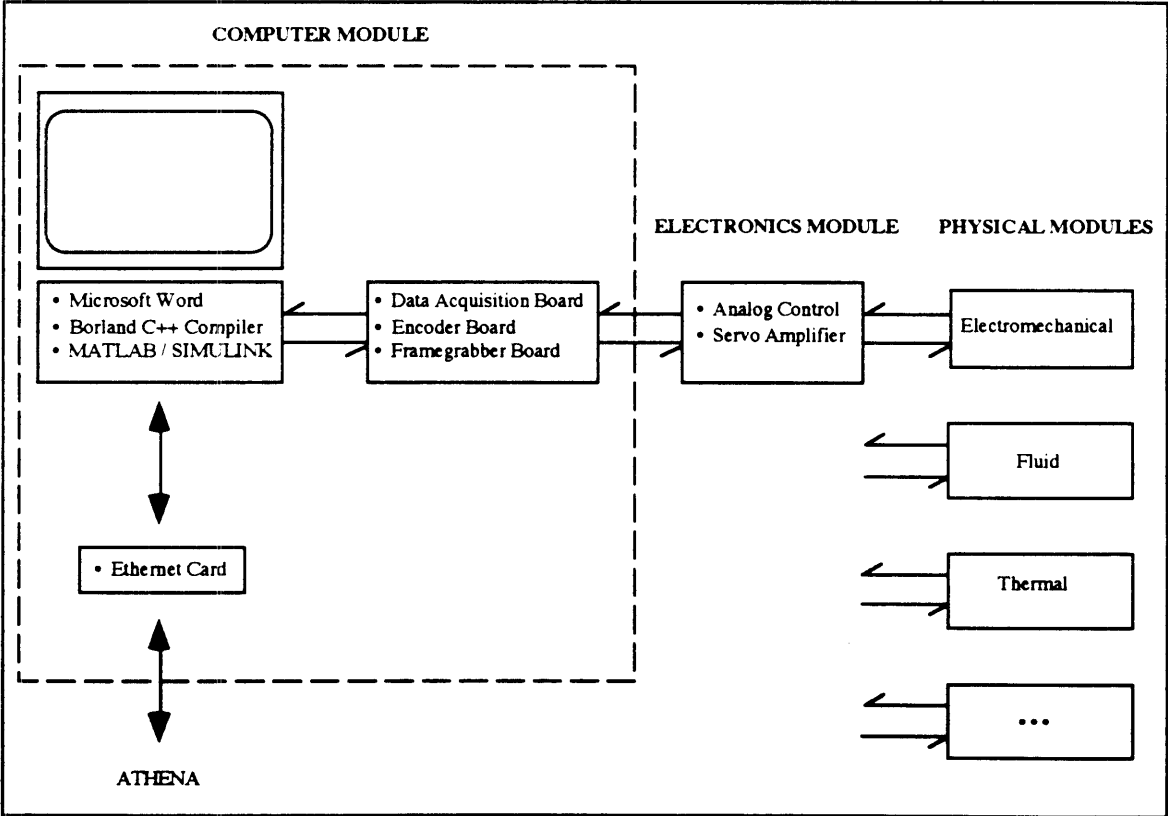
Figure 3.1: Overall System Design

Since each one of those modules has its own function, and the interaction between all three of them is made explicit, this design clarifies the steps involved to perform real-time

control. The computer module serves to perform data analysis, data acquisition, and real-time control. The electronics module serves to convert the low power signal from the computer to a high power signal which the actuator, in the physical module, needs. The electronics module also permits analog control using lead and lag compensators. The physical module is the plant being controlled. This design approach enables each module to be easily modified and integrated with other modules, thus maintaining the laboratory's vitality. The software can be quickly modified to the needs of each individual plant and its control objective. The electronics module can be altered to meet the specifications of the actuators. The physical modules can be independently replaced. The modular, open architecture approach permits graceful upgrades of software and hardware as new commercial software packages or hardware become available. Also, it will allow the integration of more complex physical systems, or the addition of physical modules illustrating other mechanical engineering disciplines. For example, a three degree of freedom manipulator control experiment could be implemented easily by simply connecting the actuators and sensors to the electronics module. This design approach establishes a high degree of short term and long term flexibility.

Having each set-up consist of a computer, an electronics, and a physical module solves the issue of one vs. several types of systems. It was mentioned in section 2.1 that having too many set-ups would prevent students from concentrating on and understanding the fundamental control theory concepts. But with this design approach, the function of the computer and electronics modules are kept constant for all set-ups, and only the physical module is replaced. Thus, it clarifies the fact that all physical systems are being controlled the same way. Alternatively, we can say that the same theory is being used to control a variety of different widgets. Another advantage to using this design approach is the drastically reduced complexity of the wiring between the various components compared to the current set-up.

3.2 Two Physical Set-Ups

To illustrate the fact that physical set-ups are easily interchangeable thanks to the modular design approach, and to reinforce students' understanding of the broad range of control system applications, two physical set-ups have been chosen for our prototype laboratory. These are a water level control system and a linear slide table, which represent two different disciplines of the mechanical engineering field (fluids and electromechanics) (Figure 3.2). In choosing to build physical set-ups from these two fields, our main considerations were: the educational validity, and the visual effects. The selected systems need to have the appropriate dynamics to illustrate the intellectual

COMPUTER MODULE

ELECTRONICS MODULE

ATHENA

FLUIDS MODULE

[S]

ELECTROMECHANICAL MODULE

[S]

ADDITIONAL PHYSICAL MODULES

[S] = Standard Connectors
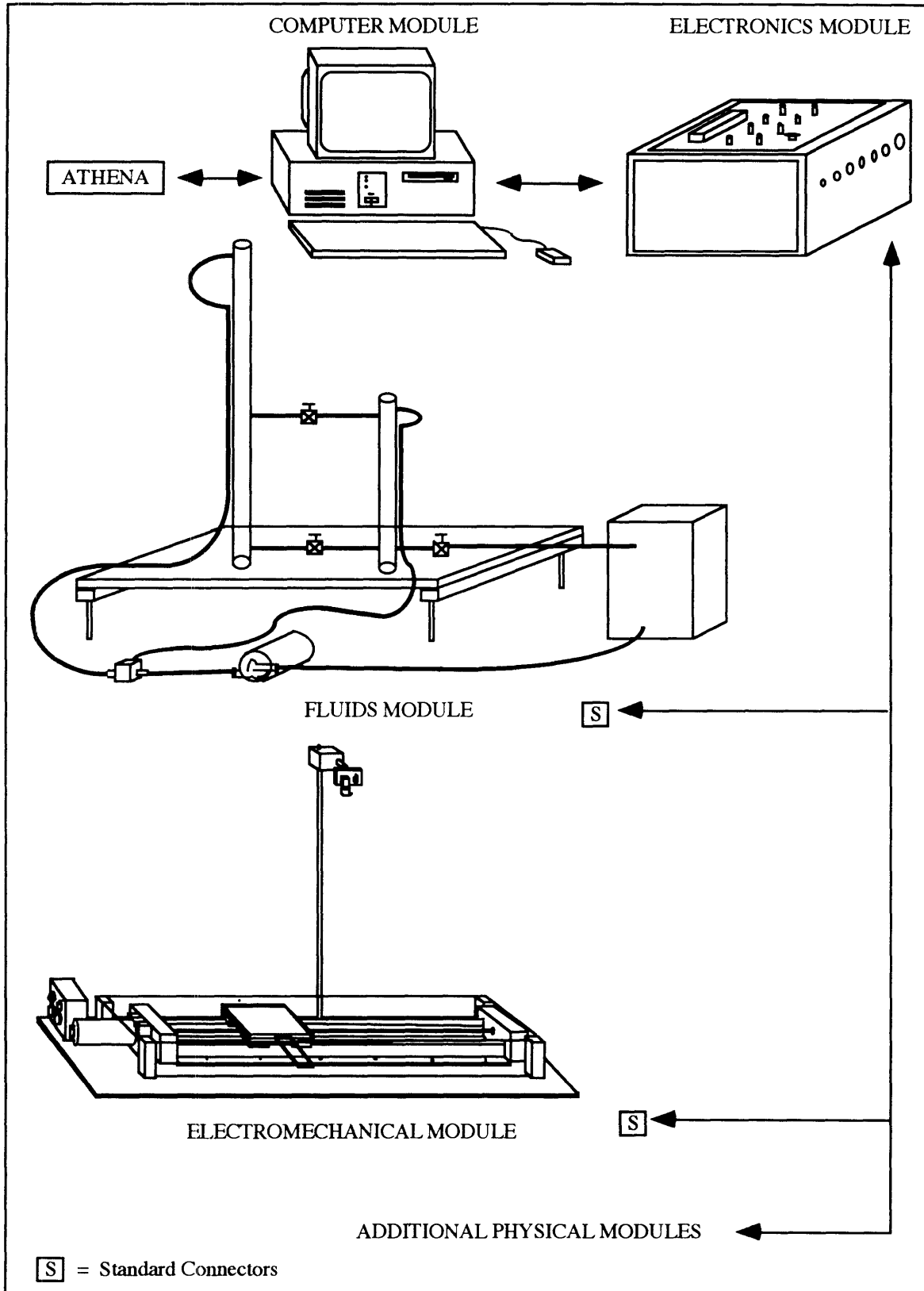
Figure 3.2: System Design

concepts listed in section 2.1. The physical state of the set-up should be readily visible in real-time. For example, a heat or thermal system was not chosen because the system response of a thermal experiment is usually not visible to the naked eye without the help of a sensor. In contrast, the water level change in a fluids system is easily visible.

Both physical plants were designed to be safe, robust to sustained student usage (and abuse), and similar to systems which students might find themselves controlling in industry later on. The electromechanical module was designed by R. Wang [48]. It is composed of a linear slide table which is a commercial product, donated by Thompson Industries, that can be representative of a variety of more complex assembly line systems in manufacturing plants. The actuator in this plant is a 24 Volt brushed permanent magnet D.C. servo motor. The sensors are an optical encoder and a CCD camera. To illustrate the dynamics of a first order system, velocity is controlled. For a second order system, position is controlled. For more detailed information about the linear slide table system refer to R. Wang's thesis [48]. Figure 3.3 depicts the completed electromechanical module.
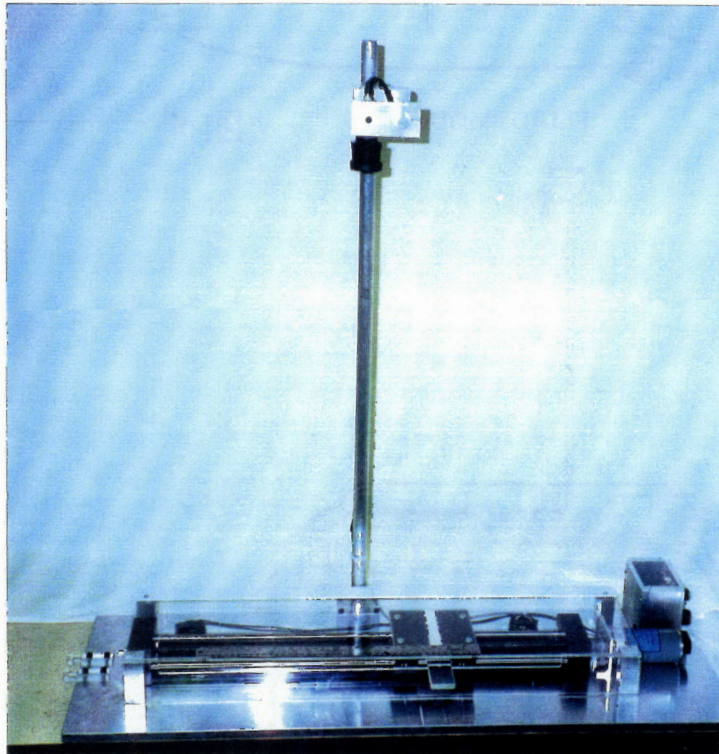
Figure 3.3: Electromechanical Module
Covering the linear slide table and the motor is a Plexiglas cover for safety. The motor and encoder are the on the right hand side of the linear slide table, and aligned with the ball screw. The CCD camera is mounted on top of the shaft and looking down.

The water level control system was designed and built in-house by German Soto and myself. Such a fluids system is representative of many process control situations taking place in chemical plants. It is composed of two tanks and a reservoir connected by needle valves. The actuator is a 12 VDC centrifugal pump, and the sensor is a pressure transducer. The fluids module allows for three different configurations: a first order system using only one tank, a second order coupled system using two tanks in parallel, and a second order decoupled system using two tanks in series. The state variable being controlled in all three cases is the water level of one of the tanks. Chapter 6 of this thesis and G. Soto's thesis [45] are dedicated to explaining the details of the water level control system. Figure 3.4 depicts the completed fluids module.
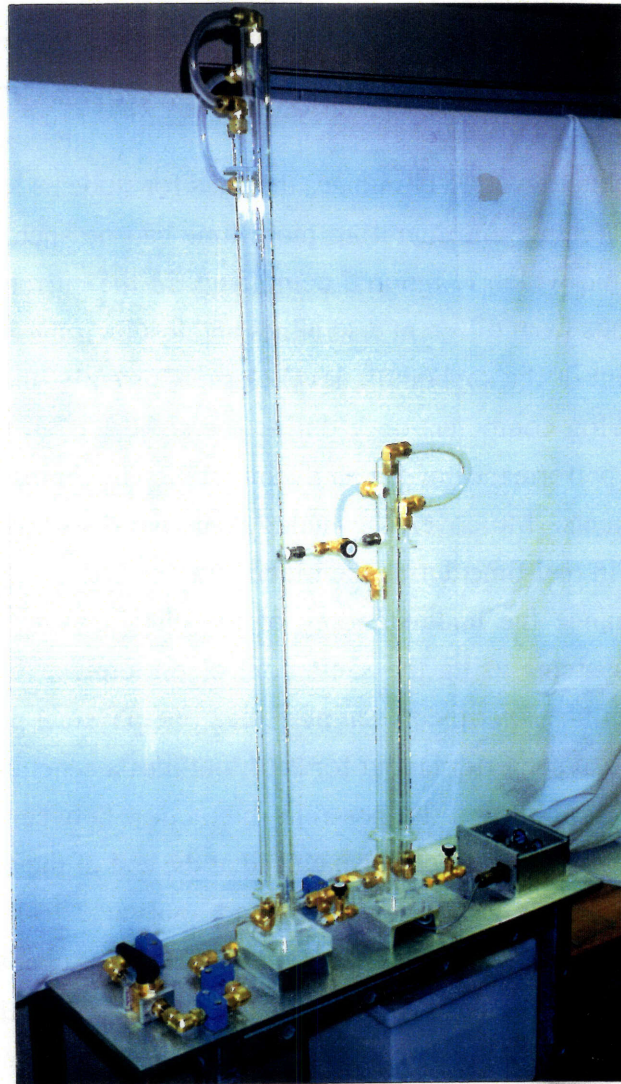
Figure 3.4: Fluids Module

The pump and reservoir are located on a shelf underneath the workbench to save space. The components which need to be visible or accessible to the students are mounted above the table top.

To study the dynamic behavior of each system, the fluids and electromechanical plants are designed to be expandable. For example, in addition to the linear slide table, the electromechanical plant has a friction device which allows the student to perform experiments with various levels of external disturbances. An inertial load can also be mounted on the ball screw of the linear slide table to change the plant's parameters. Similarly, for the water level control system, all the valve resistances along the water's path can be altered to vary the plant's parameters.

3.3 Teaching Method

We chose MATLAB, SIMULINK and the Control System Toolbox from The MathWorks Inc. as the data analysis and simulation software packages because they both integrate the laboratory into the rest of the curriculum and save time since this software package is used in other classes and most MIT students are already familiar with it by the time they take 2.14.

The modern technology used eliminates the need for students to learn the obsolete technique of analog patching, and therefore more time can be spent on more relevant issues such as modeling, which is ignored completely in the current laboratory. The students can model plants from different disciplines and test their models experimentally. This is a key component of the sophomore level class. Currently, the students simulate the plant (with the analog computer) once during the semester but never use this tool again to anticipate the performance of the hardware while performing various open loop or closed loop experiments. Moreover, the analog computer does not allow the students to analyze their results in real-time during their laboratory period.

To further enhance the understanding of the class concepts, and experience controlling different systems using the same control principles, the students will be required to perform similar experiments on more than one physical plant. Appendix D, which represents a typical semester layout for 2.14, outlines a schedule for teaching the various concepts, and exemplifies the possible interaction between the two physical modules. An individual design project was included at the end of the semester since such a project incorporates all the control concepts and analytical tools used during the semester into a single, educationally valuable experience. This schedule was developed by reviewing syllabi from several MIT mechanical engineering faculty members who have frequently taught 2.14. Though a typical MIT semester spans over 13 weeks, due to the holidays and exams there are only nine or ten laboratory sessions; Thus, most of the class material needs to be covered during those sessions. The major constraint while developing this semester schedule was to ensure that the theory will not be introduced in

the laboratory prior to the class.

An extensive graphical user interface was developed in conjunction with the laboratory handouts to lead the students through the necessary procedures [48]. Similarly, an animation program was written to illustrate the results of simulations in the most natural and intuitive way. Section 4.4 of this thesis outlines the steps taken to create the computer animation.

Finally, the laboratory material is made available to the students through the World Wide Web (WWW) on Mosaic [19]. Thanks to the hypertext capability of the WWW, an extensive set of help functions can be implemented, which serves as an on-line mentoring system for the students.

3.4 ATHENA

The distribution of laboratory manuals and the submission of student reports is done using MIT's campus-wide computer network, ATHENA. Since most MIT students regularly use ATHENA for class work, research and entertainment, and can have access to it 24 hours a day, disseminating the laboratory material through the network is what is most convenient to them. Laboratory handouts are placed on the World Wide Web, to enable students to review the material before class time. Moreover, since the programs used in the laboratory to implement the experiments (MATLAB and SIMULINK) are available on ATHENA, the students are able to perform the simulations and pre-laboratory calculations before coming to the laboratory, and import these results to the laboratory computers for comparison with the results of the physical system [19]. For example, controller gain values, determined through simulations in the pre-laboratory assignment, can then be used in the laboratory computer to perform real time control. Performing analysis and simulations prior to running the plant allows students to compare experimental and theoretical data, and understand the problems encountered due to limitations of the physical hardware in an effective manner not permitted by the current laboratory instruction method. Similarly, once the real-time control experiments have been performed in the laboratory, the experimental data can be sent directly to the student's ATHENA account for use in report write-ups. The report can then be sent electronically to the laboratory instructors for evaluation and grading. In the prototype system, however, the MATLAB Notebook Suite for Windows from The MathWorks Inc. in conjunction with Microsoft Word is used for report write-ups. Refer to section 4.5 for more details on MATLAB's Notebook Suite

Putting the laboratory computers on-line enables the laboratory to take advantage of any new software ATHENA may acquire. The possibility of future development is

therefore guaranteed.

3.5 Enhanced Effectiveness of Faculty and Student Time

As discussed in previous sections, the effectiveness of faculty and student time is increased by the use of digital computers, ATHENA, MATLAB, SIMULINK, and pre-laboratory assignments. The redesign of the laboratory not only allows more material to be covered, but results in significant time savings for the students and instructors in and outside the laboratory. The graphical user interface, which details the procedures, in conjunction with a streamlined and more efficient physical set-up, reduces the time required for each laboratory session. Currently, a laboratory session scheduled for two hours, takes on average 2.75 hours. It is estimated that with the prototype, the average laboratory time will drop to 2.25 hours, thus saving the instructors and students approximately 27 hours per semester of in class time (Appendix E). Also, using the MATLAB Notebook Suite for Windows from The MathWorks Inc., or FTP, to submit the laboratory reports will prevent the instructors from having to struggle reading every student's handwriting, therefore reducing the time spent grading. As for the current laboratory, the instructors will need to become familiar with the physical hardware, the computer interface, and the theoretical content of each laboratory assignment. However, we believe that the time spent preparing for each laboratory session is reduced. Overall, the estimated time saved for the laboratory instructors amounts to 45 hours per semester (Appendix E).

As described in Appendix E, those 45 hours can now become dedicated to another system dynamics or controls class, such as 2.02, which currently does not benefit from a laboratory component. In general, the flexibility gained from the modular design approach will allow the new System Dynamics and Controls Laboratory to be extended to serve all the sophomore and junior level dynamics and control classes which currently have no laboratory associated with them, such as 2.02 and 2.03J (Appendix A). This innovation unifies the three most important classes in the system dynamics and controls area, and thus stands as a substantial improvement in the undergraduate mechanical engineering curriculum. Moreover, since such a design approach supports more complex systems, it can also be used for graduate level classes, such as 2.151 and 2.830 (Appendix A).

3.6 Laboratory Environment

To maximize students' exposure to the physical hardware, the laboratory provides for two students per laboratory station, compared to the current laboratory that requires

three students to share a setup. The choice of two students was made to eliminate having one of the group members just sit back and observe, a trend often noticed in the current 2.14 laboratory. With three students working on the same station, the laboratory sometimes becomes more of a social gathering than an educationally valuable experience. Therefore, reducing the group size to two students aims at creating a more efficient team.

To accommodate the large enrollment in 2.14 and have two students per set-up, the total number of stations needs to be increased to eight. This will permit at the most 16 students to enroll per section, which corresponds to the maximum number of students one teacher assistant can supervise effectively. If six sections are open per semester, with this proposed laboratory format, 2.14 can hold a total of 96 students per semester.

Since there is an increase in the number of stations (from 5 to 8) in the same physical place, the floor plan of the laboratory needed to be changed. The current room is sufficiently large to accommodate 8 stations but is poorly arranged. Many tables are used to store old broken equipment. Refer to Appendix F for the proposed prototype laboratory floor plan.

A table top was designed to ease the student's usage of the computer and the physical hardware simultaneously. Refer to the Laboratory Mechanical Design Manual for the assembly drawings of the table top, which was manufactured by an outside vendor (Home Quarters) at a cost of $203.20. The general physical layout of each station can be observed in Figure 3.5. Figure 3.6 depicts the actual layout of the modules on the workbench for the water level control system. A table length of eight feet was chosen because it matches the length of the tables currently located in the 2.14 laboratory, therefore the same workbench feet can be used. A width of 15 inches was imposed on the physical module base plate to ensure the students would have a workspace area at least 15 inches deep to comfortably place a notebook. In the current laboratory, the equipment is so bulky that the students do not even have space on their workbench to place a notebook, and end up writing their reports on their laps. The size of the cantilevered piece was determined by the cross-sectional area of the computer (16.6 x 16.25 inches) and the length of the keyboard (18.9 inches).

As will be discussed in Chapter 5, the relative position of the three modules shown in Figure 3.5 was chosen to emphasize a correlation between the real system and a typical block diagram representation of a control system.

To keep the cost of developing a full scale laboratory to a minimum, it was decided that four out of the eight stations will carry one kind of physical module, and the other four will carry the other kind.
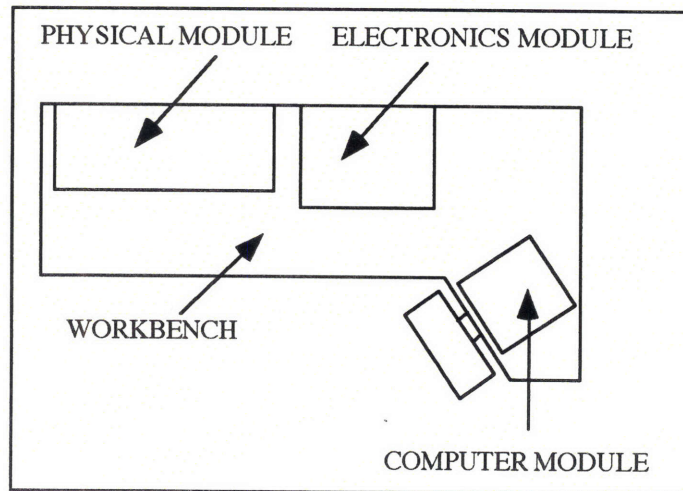
Figure 3.5: General Layout of the Three Modules on the Workbench
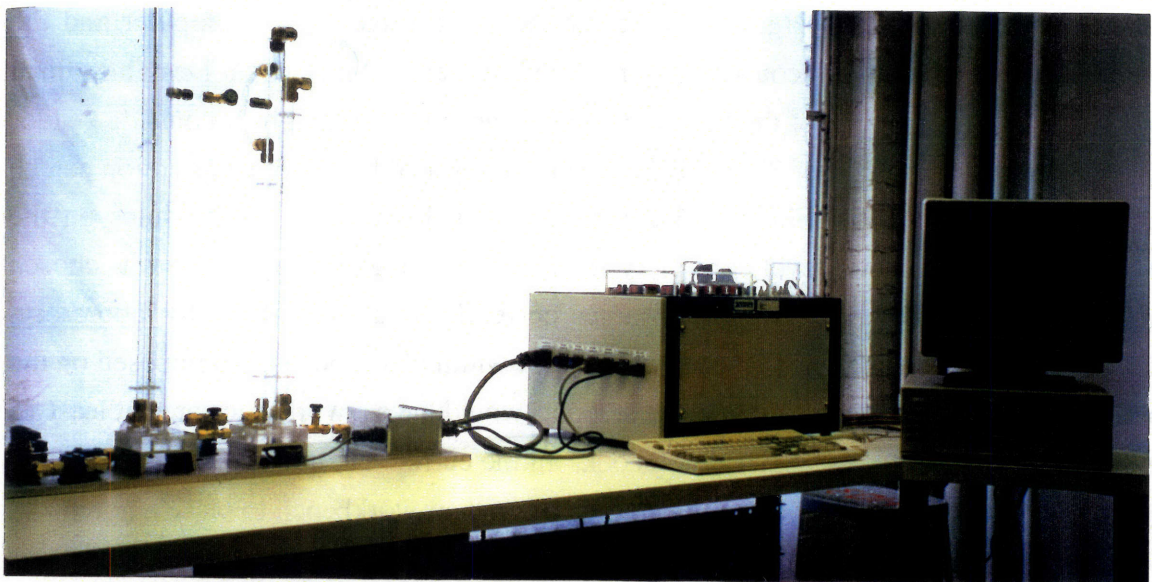
Figure 3.6: A Complete Station with the Water Level Control System
From left to right: the fluids module, the electronics module, and the computer module.

CHAPTER 4

COMPUTER MODULE

While the physical module is important for the students to view and feel the effect of each controller type, the computer module is the module students will be interacting with the most. Whether it is to send a command signal to the actuator, read the data from the sensor of the physical module, or analyze this data, the students only need to call a few programs. The construction of a user-friendly environment was undertaken on two fronts. On the one hand, the computer-student interface was designed to be user-friendly to minimize the time students will spend becoming familiar with the structure of the system. On the other hand, the computer-developer interface was kept structured, clear, and well documented to facilitate the future addition of modules or implementation of new control algorithms.

This chapter first identifies the hardware selected for the computer module of the prototype laboratory, and then outlines the software written for the real-time control, the graphical user interface, and the computer animation, the MATLAB Notebook Suite, and the use of the World Wide Web.

4.1 Equipment

The heart of the computer module is a Dell 466/MX personal computer with a 486 mother board, a DX/2 microprocessor operating at 66 MHz, a math co-processor, 20MB of RAM, 2MB of Video RAM, and 210MB of hard drive. The use of 20MB of RAM is necessary to sustain all the applications that will be running simultaneously in Windows. The fast clock speed (66 MHz) is necessary for the computational speed required by the real-time control. A 224 Watt power supply was chosen instead of the regular 150 Watt to provide for more flexibility in terms of the total power transmitted to each expansion slot. Since two students will be working on the computer, a 17" non-interlaced (flicker free) color monitor was purchased to facilitate the viewing of the many window's applications concurrently open.

This particular version of the Dell 466 was chosen for its capability to expand.

The Dell 466/MX can be configured to have up to 64 MB of RAM, and it is upgradable to a Pentium. Moreover, it contains five full-length 16-bit ISA expansion slots, which are all being used. A DATEL PC412A multifunction I/O board is used for data acquisition. It provides 16 single-ended or 8 differential analog input channels with a sampling rate of 83.3 kHz, and 12 bit A/D resolution. This board also has 4 analog output channels and 8 input / 8 output discrete digital I/O channels. This data acquisition board was chosen among the many that were evaluated from manufacturers catalog because it was the only one that supplied more than two D/A channels on the same board as A/D channels. A Digital PC7166 encoder interface board consisting of four encoder counters is used to read the encoder in the linear slide plant. A slot is reserved for the frame grabber board, Video Blaster SE 100 from Creative Labs, which is used for the vision system of the electromechanical module. Another slot is used by a graphics accelerator board for Windows and DOS applications (SpeedStar Pro from Diamond Multimedia Systems, Inc.). The monitor output is done through this VGA board which also improves the graphics capability by adding 1MB of Video RAM. The last slot is used by an Ethernet card to allow for the laboratory computers to be connected to the campus network.

Table 4.1 itemizes the cost of the computer module hardware. For a cost breakdown of the computer module that includes the price of the software refer to [48].

ITEM	DESCRIPTION	PRICE
Personal Computer	Dell - 466/MX	$3,077.00
Multifunction I/O Board	DATEL - Model #PC412A	$695.00
Encoder Board	US Digital - Model #PC7166	$150.00
Frame Grabber Board	Creative Labs - Video Blaster SE 100	$310.00
VGA Board	Diamond Multimedia Systems - SpeedStar Pro	$100.00
Ethernet Board	3COM - Model #3C509	$150.00
	TOTAL COST:	$4,482.00

Table 4.1: Cost Breakdown of Computer Module Hardware

For more information on the programs to access the data acquisition, encoder, frame grabber, and accelerator boards, as well as their usage, refer to R. Wang's thesis [48]. For more information on the programs to access the Ethernet card, refer to J. Hintersteiner's thesis [19]. Detailed specifications on each item listed in this section can be found in the Laboratory Software Manual compiled to serve as a reference manual to

the students and instructors.

4.2 Real-Time Control

All the real-time control programs were written in C, and Borland C++ was used as a compiler. The main development of the real-time control programs was done by R. Wang and J. Hintersteiner [48, 19]. This section gives only an overview of the structure of the programs.

The programs needed to run a real-time control experiment can be divided into three categories: valid for both plants and never changed, valid only for one plant and never changed, valid for one plant and can be changed.

Programs in the first category contain a set of subroutines to execute the control algorithm, as well as the configuration of the data acquisition card, and the generation of an output data file. These programs have a ".h" extension, and thus can be "included" into other C programs.

Programs in the second category are specialized since they define parameters and perform certain data conversions specific to a particular plant configuration. The programs in this category call the subroutines mentioned in the previous category, and represent the main loop of the real-time control program. These programs have a ".c" extension, and can be compiled. Thus, their executable files are called to run the real-time control.

Finally, the third category of programs is made up of files which contain a set of numbers read and outputted by the main program. Each plant configuration has two files which are read by the main program. The file with a ".cfg" extension determines the sampling frequency, the duration of the experiment, the number of loops that cycle for one data point to be recorded, and the A/D and D/A channels used. The file with a ".gui" extension summarizes the data inputted by the students in the graphical user interface. This includes the controller parameters : Kp, Ki, Kd, the type of input: step, sinusoidal or ramp, and its specification: respectively, step size [in], amplitude [in] and frequency [rad/sec], step size [in/sec]. Each plant configuration has one output file with a ".dat" extension. The data file generated has five columns representing respectively time, the actual output with respect to the initial value, the desired input, the command signal, and when appropriate the velocity.

Figure 4.1 illustrates the interaction between all those files.

For more specific information on the building blocks, or on the structure of the real-time control software, refer to [19] and [48].
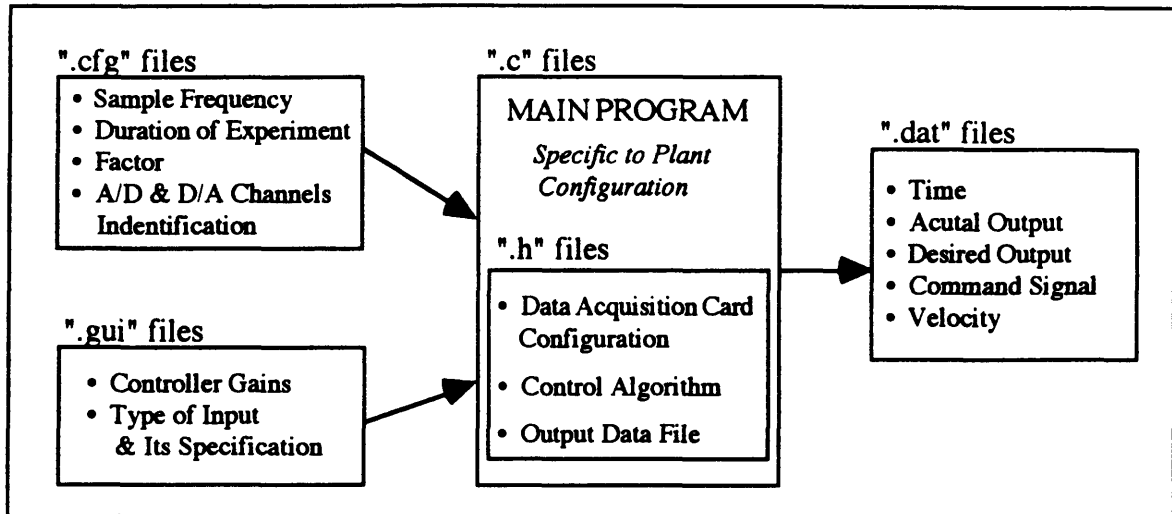
Figure 4.1: Real-Time Control Software

4.3 Graphical User Interface

An "easy" interface is important to minimize the time wasted in the laboratory. The three modules design approach tries to achieve this at the hardware level. For the computer module, an "easy" interface was accomplished using a graphical user interface, developed primarily by R. Wang [48].

MATLAB Version 4.2c was used to develop the graphical user interface (GUI). The main advantage of using MATLAB for such a task is the ability to define certain parameter values from simulation results, and have this data read by a program which subsequently will run the real-time control program. This is the data found in the ".gui" file mentioned in the previous section. Similarly, once the real-time control experiment is completed, the output is saved to a data file (".dat" file) accessible to MATLAB. This enables the student to retrieve the data and analyze it. Note, MATLAB is capable of calling any program in the DOS or Windows environment.

The GUI takes place within the MATLAB environment, thus the student does not have to become familiar with a variety of different environments, and therefore, does not have to learn complicated sets of commands to execute the programs. With a set of pop-up menus, push buttons, and mutually exclusive radio buttons, the students is led though the experiments. The GUI is meant to support the laboratory handouts and facilitate the procedures to perform the experiment. The software for the GUI is written in MFILES using Handle Graphics commands which can redefine the working environment. MFILES are files containing a set of MATLAB commands which MATLAB reads and

executes when called. Each time the students clicks on a button or chooses an item from a menu, it calls an MFILE which refreshes the figure window and displays a whole new set of buttons, commands, plots , and so forth.

For both physical plants, the structure of the GUI files is kept the same. When first starting, the students select which laboratory to perform from the "2.14 Laboratory Homepage" pop-up menu (Figure 4.2). Each laboratory has its own "Main Menu" page from which the rest of the GUI spins off. Figures 4.3 and 4.4 are examples of main menus for laboratory sessions performed on the water level control system. At the current time, the starting directory of the GUI files for the linear slide table and the water level control system is different, therefore, the module on which the student will perform the experiment needs to be predetermined to access the right directory. Figures 4.5 and 4.6 exemplify other GUI files written for the experiments on the water level control system

For more detailed information on the structure and the development of the GUI refer to [48].

A copy of all the MFILES written for the GUI of the three experiments on the water level control system can be found in the Laboratory Software Manual.
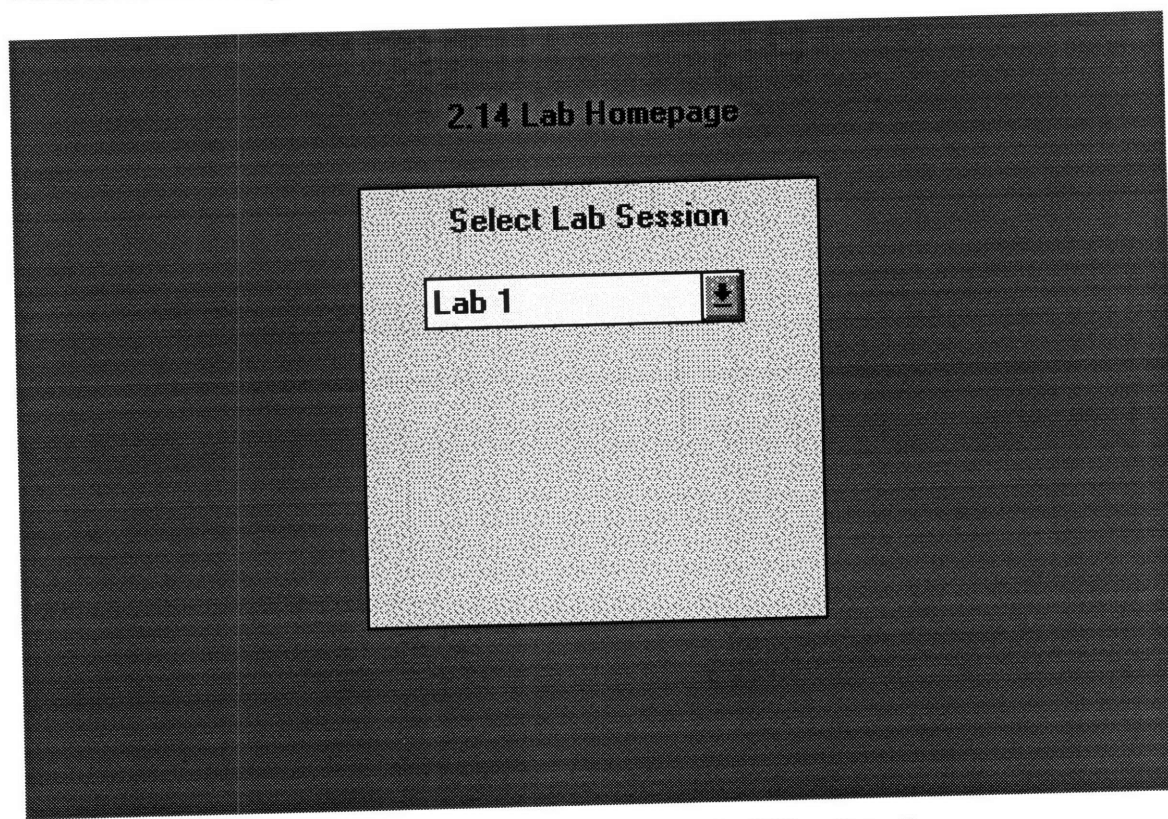
Figure 4.2: Homepage of the Graphical User Interface
Students can select the laboratory session by pressing on the pop-up menu bar, and clicking on the appropriate laboratory number.
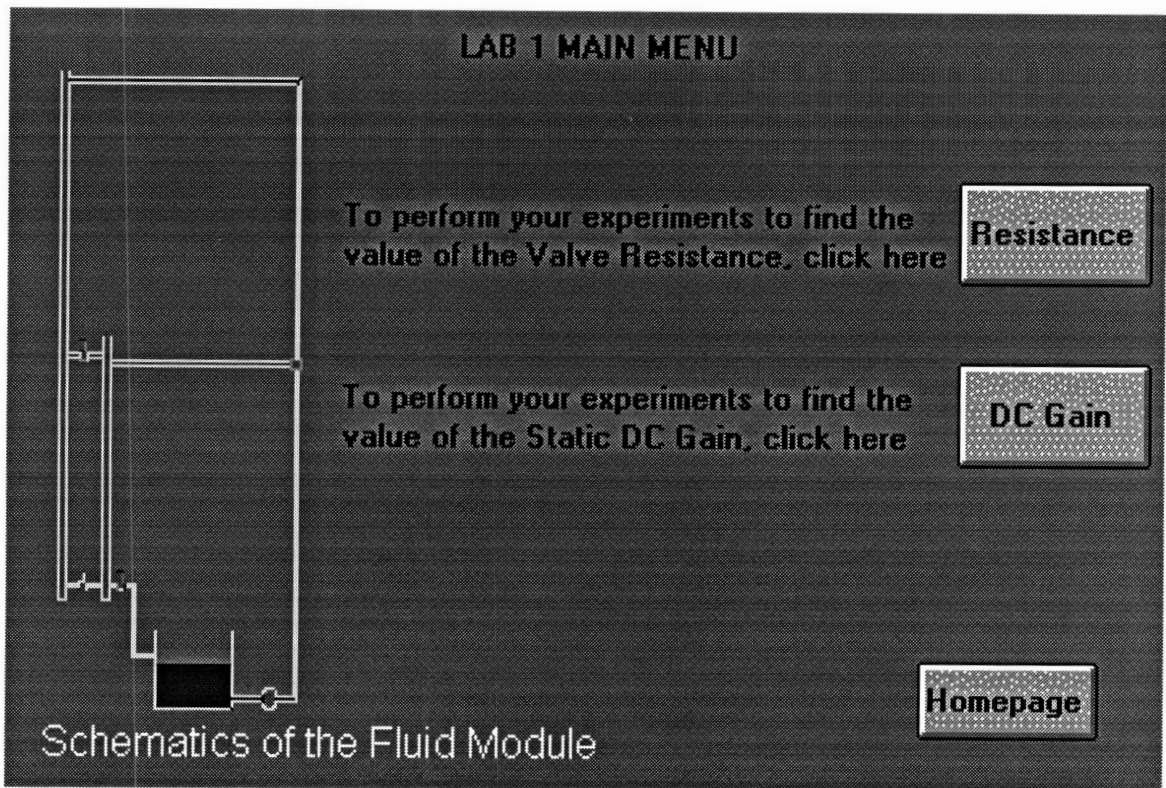
Figure 4.3: Laboratory #1 Main Menu Page
The focus of this laboratory session is on the modeling of the water level control system.
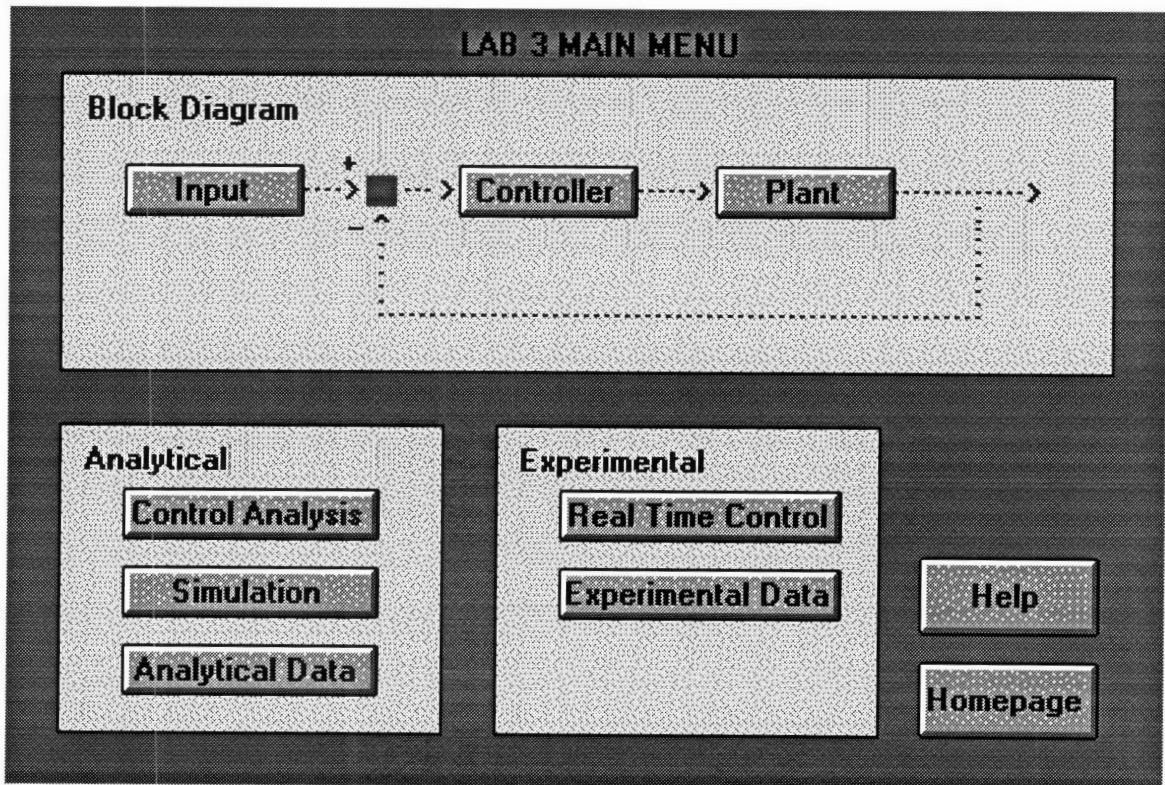
Figure 4.4: Laboratory #3 Main Menu Page
The focus of this laboratory is on open vs. closed loop control on the coupled tanks system.
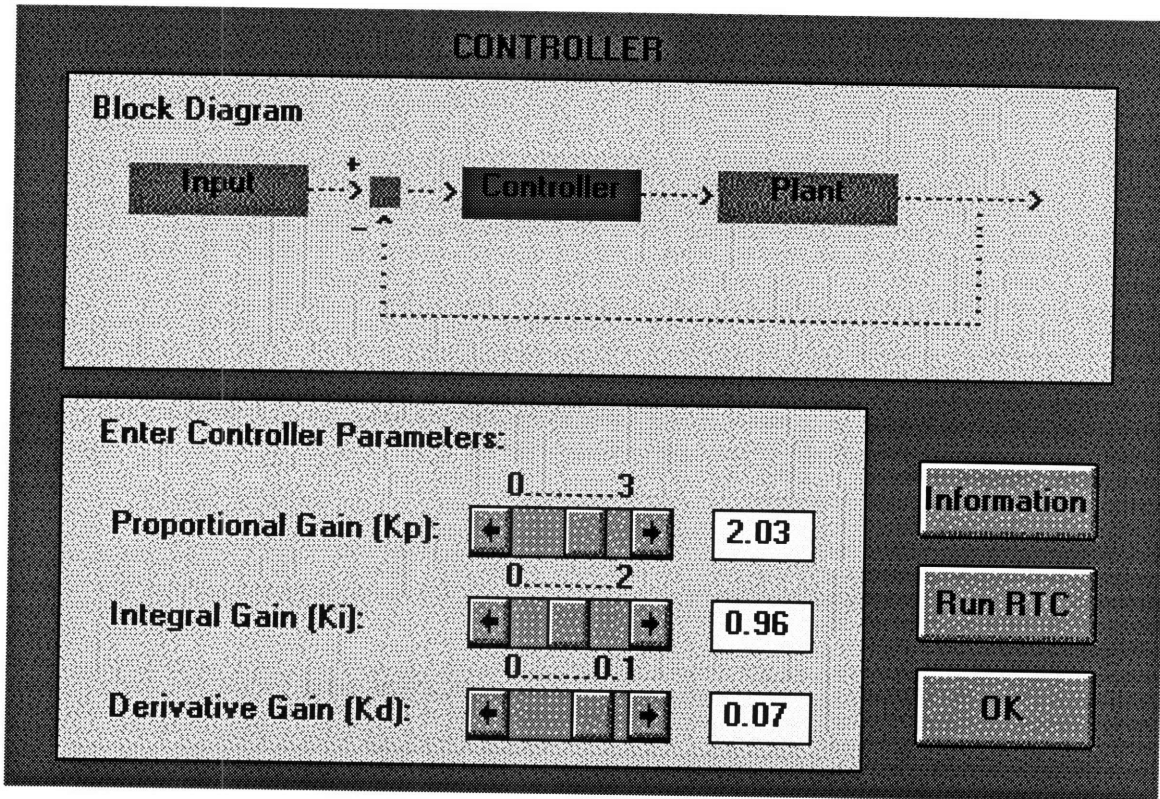
Figure 4.5: PID Controller Page

This GUI page allows students to set the value of the controller gains (Kp, Ki, Kd).
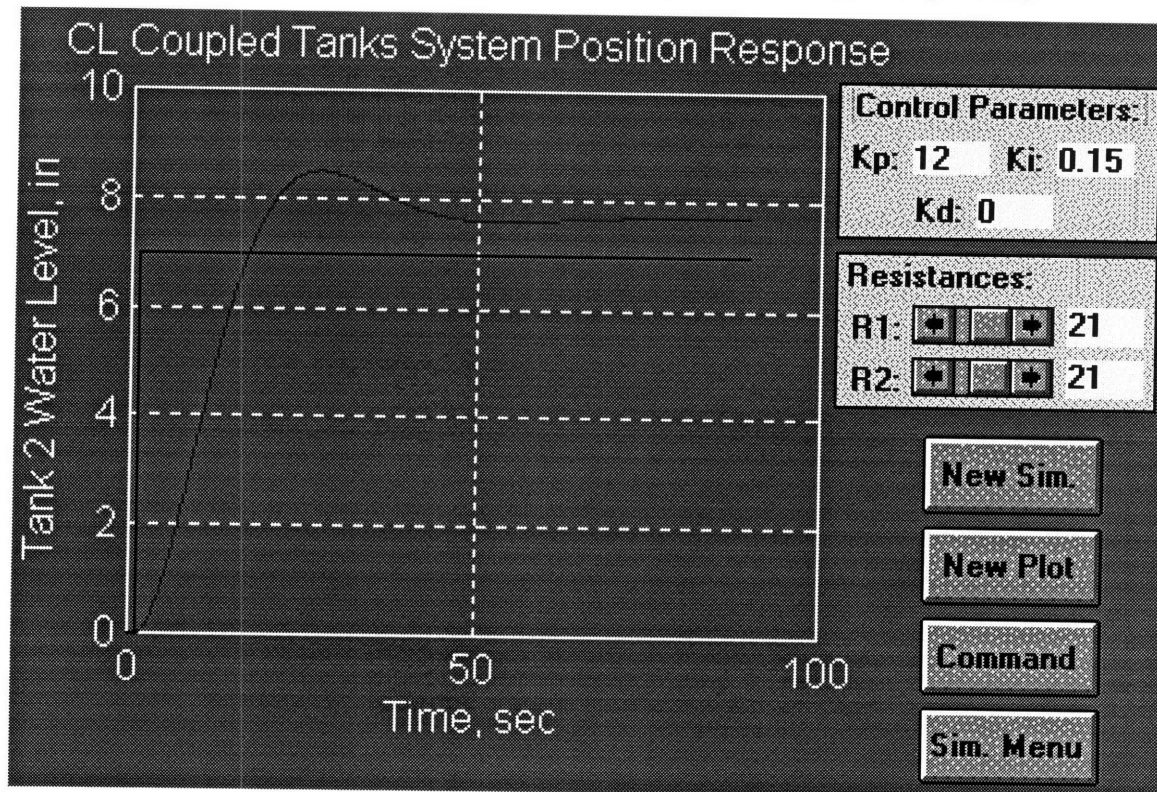
Figure 4.6: Simulation Plot Page

This page permits students to plot several simulation responses on the same graph.

4.4 Animation

The animation gives the students a graphical representation of their simulation results. The necessary programs for the animation were generated in MATLAB as MFILES to interact with the SIMULINK environment so that the animation takes place automatically while the student is simulating the plant transfer function. This means that as soon as the student has sent the command to start the SIMULINK simulation, a figure window appears on the screen and an animation takes place.

There are three steps in the programming process to create an animation. First, a schematic of the plant which is being simulated needs to be created so that the students can get a visual representation of the physical hardware on the screen (Figure 4.7). This enhances the correlation between the simulation response and the hardware response, and makes it obvious if the particular gains chosen lead to an overflow.
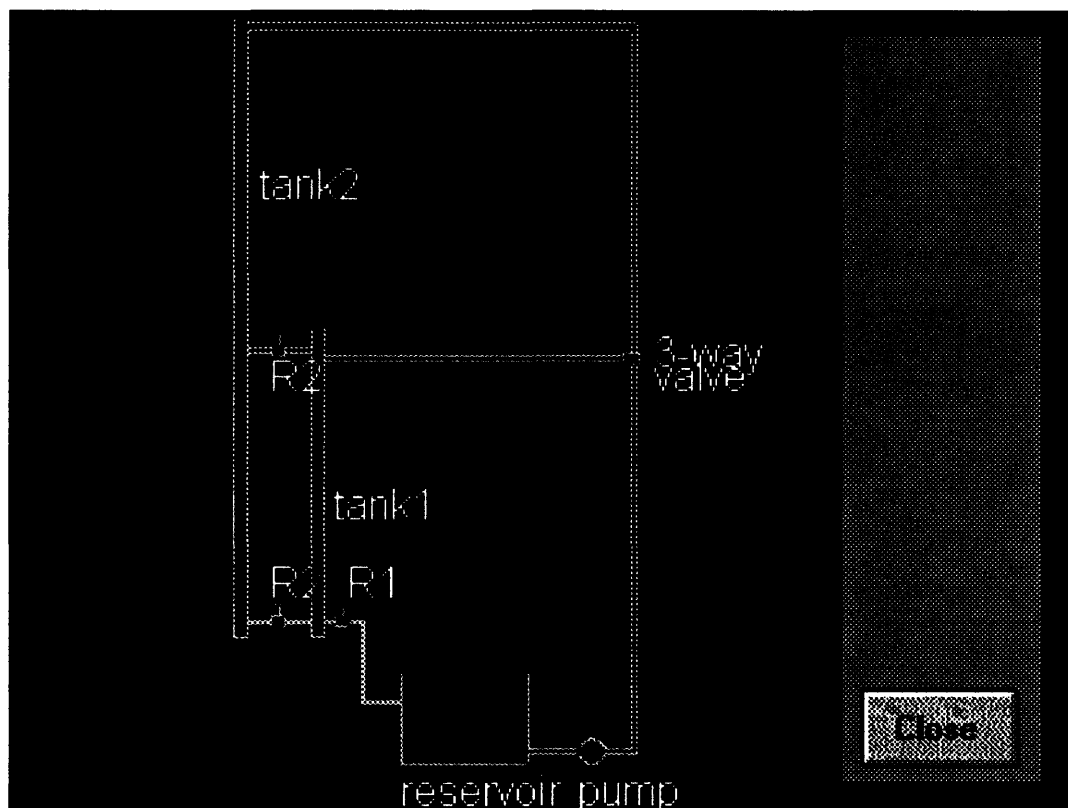
Figure 4.7: Animation Window
While the animation takes place, the students will see the water level change in the tanks.

Next, in the SIMULINK block diagram, a block, which will represent the animation program icon, needs to be added so that the output of the simulation becomes

the input of this block. Since this block is not a predefined "built-in" block in SIMULINK, a new system has to be programmed. To create a new system, one needs to define a new S-function, the agent SIMULINK interacts with for simulation and analysis, along with its function name, parameters, and position. The function name serves to identify which MFILE to call back when the animation block is triggered while the simulation is running. This MFILE represents the heart of the animation program. The number of input and output ports going in and out of this animation block also needs to be defined. Figure 4.8 represents the SIMULINK block diagram of the first order system configuration for the water level control system, and illustrates the location of the animation block.
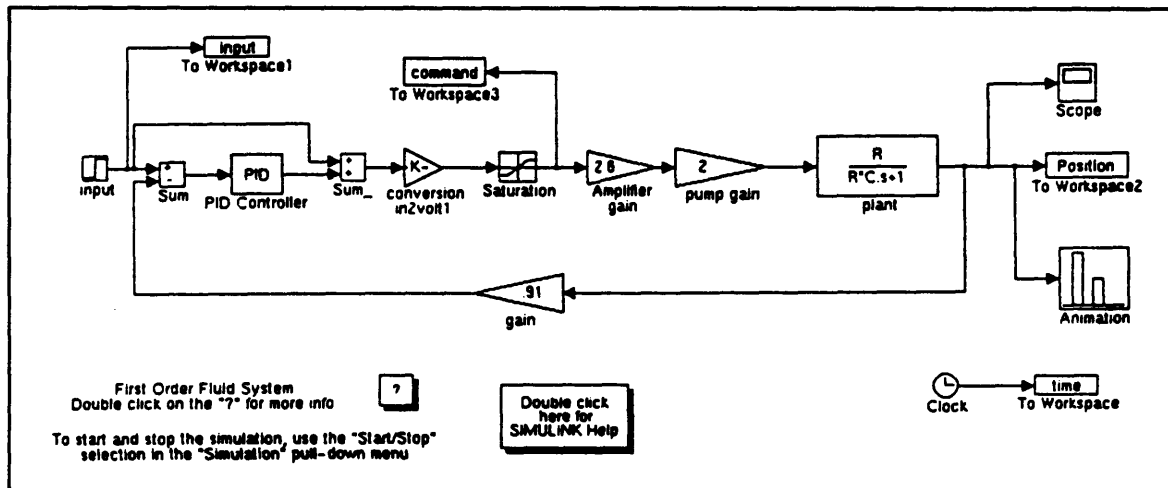
Figure 4.8: First Order Water Level Control System SIMULINK Block Diagram

Finally, the MFILE, that performs the animation and which is called when the icon previously described is activated, needs to be written. This MFILE has two main parts. The first part (flag 0) contains the initialization of the figure (window and schematic) where the animation will take place, and the definition of the command which will later be evaluated at each control loop. In the case of the water level control system, the commands defined fill the two tanks with the color blue. The second part of this MFILE (flag 2) integrates the result of each control loop to the commands previously described. Thus, for the water level control system, during the animation the tanks are filled to the appropriate level in blue.

Another means of depicting and interpreting the simulation data is to represent it on an oscilloscope. This can be achieved by using the "Scope" block, a "built-in"

SIMULINK block, which displays the output signal during the simulation. Thus, for a given system and step input, as the simulation is taking place the students have the opportunity to observe the water level go up and down in the tanks, and simultaneously see the oscillatory response on the "Scope" window.

A copy of the MFILES written for the block diagram representation, and the animation programs for the three possible configurations of the water level control system, as well as the schematic of the system can be found in the Laboratory Software Manual.

4.5 MATLAB's Notebook

The MATLAB Notebook Suite for Microsoft Windows version 1.0 is used in conjunction with Microsoft Word 6.0a to generate the students' laboratory reports which are submitted at the end of each laboratory session. The Notebook enables the user to communicate between Microsoft Word and MATLAB, and thus facilitates the transfer of data. The student can copy any parameter value and plot from MATLAB into the Word document. To achieve this transfer, the report has to be created using the M-book template in Microsoft Word. The Word document is now called an M-book and can contain text, MATLAB commands, and the output from those commands.

The format of each laboratory report should be decided by the person who writes the laboratory handouts, since the two have to be complementary. Each report includes a set of MATLAB commands which permit the students to regenerate the results found using the graphical user interface by "evaluating" those commands, and allocates space for the students to write their comments and conclusions. In some ways, the M-book is a "record of an interactive MATLAB session annotated with text" [31].

Though the idea of creating a communication link between a powerful word processor, like Microsoft Word, and a powerful analytical tool, like MATLAB, is remarkable, this version of the Notebook, which provides this link, has many bugs, some of which were reported to The MathWorks Inc. in March 1995. The problems mainly occur with the transfer of plots:

• When evaluating plots in MATLAB's Notebook, the plots are first displayed in the MATLAB figure window, copied to the Clipboard, and then brought into Word. Therefore there is no way to evaluate a plot in Word without having it appear in the MATLAB figure window first.

• Moreover, if a plot already exists in the Windows Clipboard and the MATLAB figure window is open at the same time, the old plot appears in Word while the actual plot appears in the MATLAB figure window.

- Two error messages, regarding the FormatPicture and EditPaste commands, were often encountered while evaluating plots. The former occurs when text has been copied to the Windows Clipboard and the figure window is open in MATLAB. The latter occurs when the text in the Windows Clipboard has been deleted and the figure window in MATLAB is still open.

The only way the above problems can be resolved is by closing all the open MATLAB figure windows, which in our case represents the graphical user interface. The disadvantages of closing this window is that the students will have to restart the graphical user interface from the very beginning after each plot evaluation to continue the experiment, but more importantly, all the variables will need to be redefined.

Despite the bugs, this method of submitting the laboratory reports was chosen because the Word environment is know to most students and easy to use. Moreover, cutting and pasting the MATLAB figure window onto Word is possible, and reproduces the plots without having to "evaluate" them. Therefore, the MATLAB Notebook Suite permits to save all the necessary laboratory results and incorporate them in a report which is submitted at the end of each laboratory session. The MATLAB Notebook Suite being used in the prototype System Dynamics and Control Laboratory is the first commercial version. Thus, most of those problems should be solved in future versions.

4.6 World Wide Web

As mentioned in section 3.4, the distribution of the laboratory handouts to the students is done using the World Wide Web (WWW) through Mosaic. Since the main objective was to enable the students to perform the pre-laboratory assignments at their own convenience, and review the laboratory handouts prior to the laboratory session, putting the laboratory material on-line was an obvious choice. It could have been placed, however, in a read-only locker which can be accessed by any student, but the WWW method of dissemination was chosen because it is a more interactive environment. Mosaic has an extensive hypertext capability which can be used, through links, to provide help and references to the user. Moreover, Mosaic is supported on the campus-wide computer network ATHENA. Therefore, if students have any questions or problems, they can get help on-line very easily. In addition, the WWW, rather than Microsoft Word, was chosen as the way of viewing the laboratory material while in the laboratory because it facilitates upgrades. Instead of updating the files both on ATHENA and on Microsoft Word, it can be done once by updating the WWW files.

The WWW URL address for the prototype System Dynamics and Controls Laboratory is: "http://me.mit.edu/2.14/."

The structure and content of the WWW files and links, except for the laboratory handouts, were developed by Jason Hintersteiner, and you should refer to his thesis for more information on the topic [19].

CHAPTER 5

ELECTRONICS MODULE

The electronics module serves to incorporate, into one compact box, all of the electrical components which power the plant's actuators and sensors, and transmit the signal from the sensors to the computer module. The electronics module represents a bridge between the computer module and the physical module. This is why, as presented in Figure 3.5, the electronics module is physically located between the other two modules. The goal is to emphasize a correlation between a typical block diagram students often encounter in the class lectures, and the physical layout of the modules on the workbench. Figure 5.1 illustrates this correlation. Moreover, enclosing the various electrical components into one box not only ensures a clean presentation, but also avoids the confusion on the function of each item.
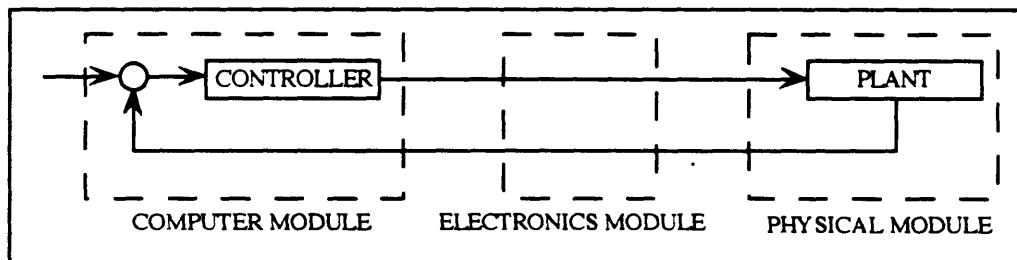
Figure 5.1: Correlation Between Physical Layout and Typical Block Diagram

This chapter outlines the function and selection process of the major components of the electronics module. An overview of the design criteria for the intellectual requirements, safety measures, and practicality are also given. This is followed by a description on how those design criteria are physically implemented. All the relevant schematic diagrams, assembly drawings, and circuit diagrams which give an overview of the final design of the electronics module are included. Then, the interactions between the electronics module and the other two modules (computer and physical) are described.

A discussion on the upgradability of the electronics module follows. Finally, a cost breakdown of the electronics module is presented.

5.1 Major Components and Their Functions

The electronics module is made out of a large number of components such as: power supplies, servo-amplifiers, a filter card, screw terminals, dual binding posts, banana plugs, connectors, switches, an "Emergency stop" push button, op-amps, and quad op-amps. For a more comprehensive list of the components and their manufacturer, refer to section 5.6. In this section, only the function and selection process of the servo-amplifiers, power supplies and filter card is discussed.

Servo-Amplifiers

The function of a servo-amplifier is to amplify the low power signal coming from the controller output to a high power signal. In the case of the prototype System Dynamics and Controls Laboratory, the low power signal comes from the multifunction I/O board located in the computer, which can output between -5.0 to +4.9976 Volts at a few milliamps. The high power signal goes to the actuator, which for the fluids module is rated at 12 VDC and 3 Amps.

Since it was decided that the prototype System Dynamics and Controls Laboratory will include both a fluids module and an electromechanical module, the goal was to find a servo-amplifier that would serve the needs of both plants. Each one of these modules has one actuator. For the fluids plant, the actuator is a 12 VDC pump, and the flow rate needs to be controlled. Ideally, there is a linear relationship between the speed (RPMs) and the flow rate. Therefore, a voltage-to-voltage amplifier is required. On the other hand, for the electromechanical plant, the actuator is a 24 VDC motor, and the torque rather than the speed needs to be controlled. Thus, for the electromechanical plant, a voltage-to-current amplifier is needed. Therefore, a servo-amplifier that can operate in both modes was selected. For convenience though, the decision was made to purchase one servo amplifier per actuator.

The motor driving the pump head in the fluids module, as well as the one used in the electromechanical plant, is a brush type DC motor. So, the servo-amplifier needs to be designed to drive such motors. Moreover, to facilitate future upgrades, the calibration of the servo-amplifier needs to be achieved easily. Some of the other criteria taken into consideration while selecting the servo-amplifier were the maximum continuous current and peak current, the switching frequency, the internal safety measures, the required power supply voltage, the size, and the cost.

After careful evaluation of many linear and pulse-width modulated (PWM) servo-amplifiers, the Advanced Motion Controls 25A8 model was selected [2]. This servo-amplifier model is a PWM servo-amplifier designed to drive brush type DC motors at a switching frequency of 33 kHz (Table 5.1). By means of a DIP switch, this servo-amplifier can be set to operate under four modes: current mode, voltage mode, IR compensation, or tachometer mode. Thus, this servo-amplifier model can be used for both actuators. By tuning four 15-turn potentiometers, the loop gain, current limit, reference gain, and offset can be relatively easily adjusted to match any actuator which meets the power specifications of the servo-amplifier (Table 5.1). This ensures that the modularity of the electronics module is maintained. For further information on the calibration procedures for a voltage-to-voltage or voltage-to-current amplifier, refer respectively to Chapter 6 of this thesis or R. Wang's thesis [48].

DC SUPPLY VOLTAGE	20 to 80 V
PEAK CURRENT (2 sec. max., internally limited)	± 25 Amps
MAX. CONT. CURRENT (internally limited)	± 12.5 Amps
MINIMUM LOAD INDUCTANCE	200 μH
SWITCHING FREQUENCY	33 kHz

Table 5.1: Power Specifications for the 25A8 PWM Servo-Amplifier*

The DC supply voltage, in Table 5.1, represents the power input range within which this servo-amplifier model can operate. The input needs to come from an unregulated DC power supply, whose selection will be discussed later.

The internal safety measures of the 25A series PWM servo-amplifier model protect the system against over-voltage, over-current, over-heating, and short circuits across the motor, grounds, and power leads, which results in a robust system.

For the functional block diagram of the 25A8 PWM servo-amplifier, or to obtain more information on the power, input, output, and mechanical specifications, as well as the detailed pin functions, and mounting dimensions, review the *Advanced Motion Controls PWM Servo Amplifiers Catalog* [2].

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* Partial reproduction of the *Advanced Motion Controls PWM Servo Amplifiers Catalog* [2].

Power Supplies

The electronics module has two power supplies. One serves to power the sensors and op-amps, and the other serves to power the servo-amplifiers described above.

The sensors and op-amps need a low power input signal for excitation purposes. Thus, the power supply selected to provide this excitation is a DC power supply which outputs +12 V at 500 mA, -12 V at 500 mA, +5 V at 2.0 mA, and common. This power supply is manufactured by Elpac Power Systems and was selected for it compact size and low cost [36].

While choosing the power supply for the servo-amplifiers, the modularity and expandability of the laboratory were kept in mind. The total power provided by the power supply should be sufficient to power more than one servo-amplifier and actuator at a time, even though the prototype system only uses one at a time. The power supply chassis should have the capacity of hosting more than one servo-amplifier. But first and foremost, the power supply should meet the needs of the actuators used in the fluids and electromechanical plants.

According to the Set-Up Instructions and Application Notes in the *Advanced Motion Controls PWM Servo-Amplifiers Catalog* [2].

- The maximum power supply voltage should be calculated from the Voltage Constant (Ke in V/kRPM) times the maximum motor speed.

- The maximum power supply current should be calculated from the maximum torque divided by the Motor Torque Constant (Kt in lb-in/Amp)

- In general, it is recommended to select the power supply voltage to be about 10 to 50% higher than the maximum required voltage for brush type motors.

Table 5.2 shows the calculations for both actuators.

Since the actuator in the electromechanical plant has higher voltage and current requirements than the actuator in the fluids plant, the former imposed the selection of the power supply. The PS1200W-40V unregulated DC power supply model from Advanced Motion Controls was selected, not only because it meets the minimum voltage and current supply, but also because this model can host up to six of the 25A8 servo-amplifiers previously mentioned. The PS1200W-40V can supply a maximum of 40 VDC at 40 Amps continuous.

ELECTROMECHANICAL PLANT*	FLUIDS PLANT**
(24 VDC actuator)	(12 VDC actuator)
Voltage Constant Ke = 11.0 V/kRPM	Voltage Constant Ke = 2.9 V/kRPM
Rated Speed = 2200 RPM	Maximum Speed = 4000 RPM
Torque Constant Kt = 14.8 in-oz/Amp	Torque Constant. Kt = 3.92 in-oz/Amp
Peak Torque = 350 in-oz	Stall Torque = 82.8 in-oz
Power Supply Voltage for Rated Speed 11 E-3 * 2200 = 24.2 V	*Maximum Power Supply Voltage* 2.9 E-3 * 4000 = 11.6 V
Maximum Power Supply Current 350 / 14.8 = 23.65 Amps	*Maximum Power Supply Current* 82.8 / 3.92 = 21.12 Amps
Recommended Power Supply Voltage 24 + .5 * 24 = 36 V	*Recommended Power Supply Voltage* 12 + .5 * 12 = 18 V

Table 5.2: Power Supply Selection for the Servo-Amplifiers

Another recommendation, according to the Set-Up Instructions and Application Notes in the *Advanced Motion Controls PWM Servo-Amplifiers Catalog* [2], is to select an amplifier with a voltage rating at least 20% higher than the maximum power supply voltage to allow for the regenerative operation and power supply variations. As stated Table 5.1, the voltage rating of the selected amplifier (model 25A8) is from 20 to 80 VDC which is 50% higher than the maximum power supply voltage. Moreover, it is recommended that the amplifier current rating (± 25 Amps Peak, - Table 5.1) should exceed the maximum motor current requirements (24 Amps at Peak Torque*). This shows that the PS1200W power supply and the 25A8 servo-amplifier are a good combination for the actuator on the electromechanical module.

Both power supplies mentioned in this section require a 120 VAC input at 60 Hz.

Filter Card

Though the power supply PS1200W is appropriate for the electromechanical plant

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* Data obtained from Servo Systems Co. [44].

** Data obtained from the motor manufacturer of the pump: RAE Corporation, and represents performance of motor without load (i.e. without the pump head). Refer to the Laboratory Mechanical Design Manual [46].

actuator, it is too powerful for the fluids module actuator which should not have a power supply providing more than 20 VDC (Table 5.2). Having too high of a power source will cause commutator problems due to the pulses of the PWM servo-amplifier output. This problem can be eliminated by adding a filter card between the servo-amplifier output and the actuator input. The function of the filter card is to increase the load inductance of the motor, and to smooth out the pulses going into the motor.

The model FC10010 filter card from Advance Motion Controls was selected. It contains two 100 μH inductors rated at 10 Amps.

5.2 Design Criteria

The components described above represent the heart of the electronics module. Connected in the proper way, they are sufficient to activate the sensors and operational amplifiers, and power the actuators. The issue now is to combine them in a clean and orderly way which meets the intellectual requirements, has safety measures, and is practical.

Intellectual Requirements

This section discusses the intellectual requirements of the electronics module by answering the following three questions: Should analog control be integrated in this module and how? Which components should the students see? Which ones should they have access to?

Analog Control Loop

Based on discussion with the faculty, the prototype System Dynamics and Controls Laboratory includes an analog control loop. Since the current undergraduate Control Systems Laboratory does not include lead or lag compensators, it was decided that the analog control loop will be able to correct this shortfall. Now, the issue became how to implement it. Two methods of implementation were considered. The first option would have the students go back to working on the Comdyna. The second option would have the students build their own analog circuits on proto-boards.

Since the majority of the students do not enjoy working on the Comdyna, and get confused by it, this option was rejected. Teaching students how to build an analog circuit using op-amps is currently not included into the curriculum of any mechanical engineering system dynamics or controls course, and was argued to be too large of a deviation from the class material to validate its presence in the laboratory. Moreover, though most seniors would have been introduced to analog circuits by the time they

enroll in 2.14, it is safe to say that more than 70%* of the students enrolled in 2.14 in any given semester would not know, or at least remember, anything about it. Thus, without spending time teaching the students analog circuits, the second option is not feasible.

As a compromise between having the students work on the Comdyna, and build everything from scratch, the following concept was adopted: A fully assembled analog circuit representing a lead/lag compensator, built on a proto-board, would be provided to the students. Thus, the students are not required to design or assemble any circuit. However, to ensure some modularity to the compensator, all the resistors and capacitors can be changed. Refer to section 5.3 where more detailed information on the implementation of this analog control loop can be found.

Now You See It ... Now You Don't

In the current undergraduate controls laboratory, though the servo-amplifier is obviously placed on the workbench, the students never touch it, nor do they even worry about its existence except to turn on the switch which "miraculously" powers the motor. So, the educational value of having the servo-amplifier visible to students was considered. At the level of an undergraduate System Dynamics and Control Laboratory, it was judged unnecessary for the students to be confronted with hardware which they do not understand, and do not need to learn within the context of this laboratory. Thus, it was decided that the servo-amplifiers, along with their power supply, and the filter card will be hidden from the students.

Since the objective is not to label the electronics module as a black box, but rather to design a tool more easily understood by students with a limited electrical background, some connections were deemed important to present to students and therefore to keep visible. The servo-amplifier takes its input signal from a D/A channel on the multifunction I/O board, and outputs the signal going directly to the actuator, so all connections, from the computer module to the electronics module, and from the electronics module to the physical module, are displayed. The lead/lag compensator analog circuit mentioned above is composed of op-amps which need an input voltage of ±12 V to be activated. Therefore, the connections which enable students to power this analog circuit are also visible. However, the power supply which outputs the ±12 V, +5 V and common has no educational value, and can be hidden along with the other power supply, the servo-amplifiers, and filter card.

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* Estimate from student feedback when asked about op-amps.

From this discussion, one can notice that the components previously described as representing the heart of the electronics module are hidden from the students. Though those components are necessary to power all the components existing in the electronics and physical modules, the understanding of their inner workings is an overhead to the understanding of control theory. Therefore, the two servo-amplifiers, the filter card, and the two power supplies can be placed in an enclosed area labeled "Power Source" without losing the educational value of the laboratory.

Can't Touch This

Safety is a primary design consideration. The issue of how much freedom the students should be given to tamper with the wires and increase the risk of short circuits, ground loops, and shocks needed to be evaluated. For example, in the current undergraduate Control Systems laboratory, some of the wires from the servo-amplifier output to the motor input are exposed and sometimes get loose. A student can inadvertently connect the common to the high power signal relatively easily.

To protect both the students and the equipment from hazards, some prevention measures were taken in the prototype System Dynamics and Controls Laboratory. It was decided that students should not have access to any of the connections between the computer module and the electronics module, though, as mentioned earlier, they should be able to see them. This was achieved by designing a Plexiglas box which screws onto the panel those connectors are mounted on. This decision was taken on the basis that none of those connections will ever need to be altered except for repairs or upgrades, which should only be done by an instructor or a future developer.

Given a physical module, the connections between the electronics module and the physical module are not change. However, the prototype System Dynamics and Controls Laboratory has one electronics module for two physical set-ups, which means that those connections need to be interchanged depending on the physical set-up in use. Therefore, for convenience, those connections should be easily accessible. The same thing can be said about the connections which provide power to the lead/lag compensator analog circuit, since in that case, the students need to make the connections themselves.

Additional Safety Measures

An "Emergency stop" push button has been integrated in the design to permit the students to shut off the power going to the actuators, and is located in an obvious place easily reached on the top panel of the electronics module.

As an added safety measure for the A/D channels of the multifunction I/O board,

a unity-gain follower is used to buffer the analog sensor signal from the physical module to the computer module. This buffer prevents voltages beyond the ±12 VDC range to enter the multifunction I/O board.

All the commons are interconnected, and connected to earth ground. Moreover, the chassises of both power supplies are grounded, as well as the box representing the electronics module.

All the connectors in the electronics module are keyed so that they can be inserted in only one way.

No loose wires were left unsecured, especially in the area students will work on the most. The only connections students have to do are with banana wires, except if they want to change resistors or capacitors in the lead/lag compensator analog circuit (see section 5.3).

Electrical tape is used to cover any area that might, if a wire drops by accident, create a hazard. Those areas are the metallic areas left open on the screw terminals and on the capacitor and the transformer of the servo-amplifier power supply.

All the wires running from one module to another are strained-relieved or clamped to withstand being pulled on accidentally by students.

Practicality

To implement the idea of having some components visible, and other hidden, using a cabinet for the electronics module seemed to be an obvious choice. The hidden components are located inside the cabinet, and the visible ones are located on the top or side panels of the cabinet. In-house modifications of the cabinet had to be performed to allow for all the components to be mounted. Thus, for ease of machining, a cabinet with removable panels was desired. Among the several manufacturers and vendors of cabinets, Zero Stantron instrumentation cabinets were the only small size cabinets which had this feature [50].

When the assembly of all the components took place, all of the panels were kept independent. Before connecting any wire between a component on one panel to another component on another panel, each wire goes through a connector or a screw terminal. This facilitates the disassembly of the electronic module for maintenance, calibration, upgrades or repairs.

The connections between the computer and electronics module are made on the right side of the top panel's cabinet in order to emphasize the correlation between the physical layout of the workstation and a typical block diagram (Refer to Figure 5.1). As a result, they are visible, but not accessible due to a Plexiglas cover. The connections

between the electronics and physical module are made on the left side panel. No connectors were mounted on the front panel for two reasons: First, to avoid tempting students to play with them; and second, to prevent taking too much of the student's working space area.

5.3 Implementation

Now that the general guidelines of the electronics module design criteria have been set, this section describes its implementation.

Overall Mechanical Design

The multifunction I/O board, as described in section 4.1, provides for four D/A channels and 16 single ended or 8 differential A/D channels. The electronics module is designed to control up to a four degree of freedom system. Thus, it can serve the needs of the current undergraduate Control Systems Laboratory, where students do not control more than one actuator at a time, and ensures an open-architecture for future expansion. To implement a four degree of freedom system in the most complex case, the electronics module accommodates four D/A channels controlling one actuator each, four differential input A/D channels for the analog sensors, and four encoder channels.

Because op-amps saturate if their input power is too high, room was left for the analog control loop circuit to be plugged in before the low power signal from the D/A channels goes to the servo-amplifiers.

Figures 5.2 and 5.3 represent, respectively, the front view and top view schematic drawings of the electronics module. Figures 5.4 and 5.5 show the realization of the final electronics module design. Following is an explanation of the path taken by the signal from the computer to the actuator, and from the sensor to the computer.

Path of D/A Signal

The cable bringing in the D/A signal from the computer module is split into four channels. As illustrated in Figure 5.3, after the split, there are four rows of dual binding posts, which from right to left represent the D/A signal from the computer, ±12 V, +5 V and common, the input to the servo-amplifiers. The reason for those four rows of dual binding posts is to provide space and power for the lead/lag compensator analog circuit to be plugged in prior to the servo-amplifiers. The two dual binding posts outputting ±12 V, +5 V, and common, are necessary to power the op-amps on the analog circuit. The implementation of the lead/lag compensator analog circuit will be covered in more detail later in this section. The output of the servo-amplifier, or filter card as appropriate, is

linked to a connector on the left side panel of the electronics module (Figure 5.2). The signal is then transmitted to the actuator in the physical module through a cable.
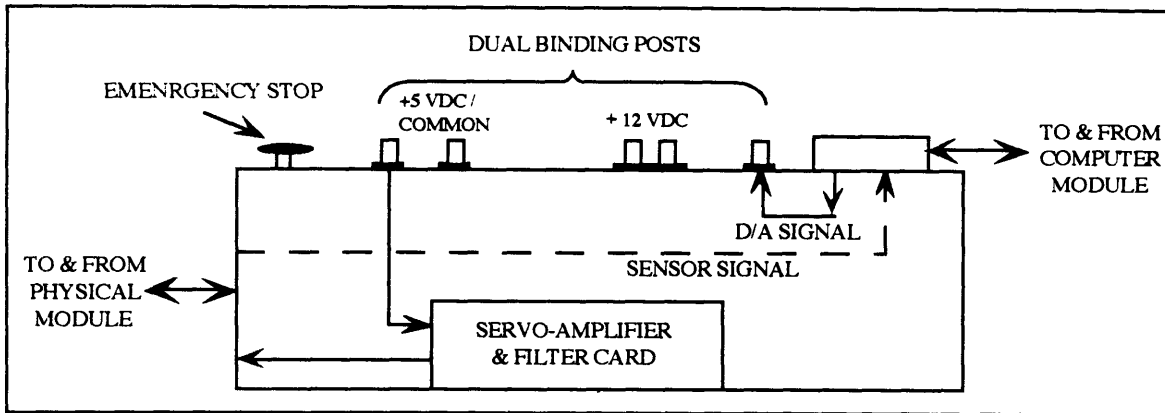
Figure 5.2: Front View Schematic Drawing of the Electronics Module
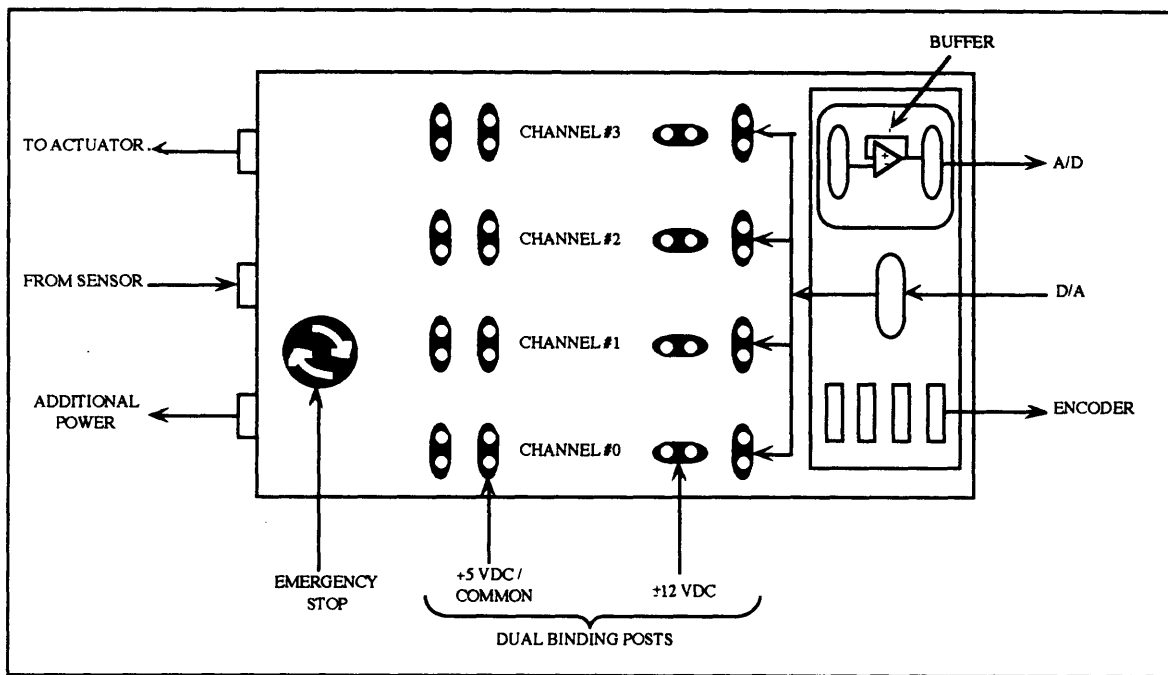
Figure 5.3: Top View Schematic Drawing of the Electronics Module

Path of Sensor Signal

A cable from the physical module transmits the sensor signal to the electronics module. The sensor signal is by-passed in the electronics module, which means that no

signal conditioning of the sensor signal is done on the electronics module, but rather at the physical module level. Signal conditioning may need to be used on the analog sensor signal to match its range with the rated full scale input range of the multifunction I/O board (±5 V). Moreover, when a signal travels any distance it is subject to noise. If the sensor and noise signals are of comparable magnitude, the data read by the multifunction I/O board will not be accurate. To avoid encountering this problem, the sensor signal is conditioned at the physical module level. The signal coming from analog sensors goes through a unity-gain follower which serves as a buffer (Figure 5.3). This buffer prevents voltages which exceed the input overvoltage range for no damage of the multifunction I/O board (±12 V) to be sent to the board. There are no protection circuits implemented on the digital sensor line.
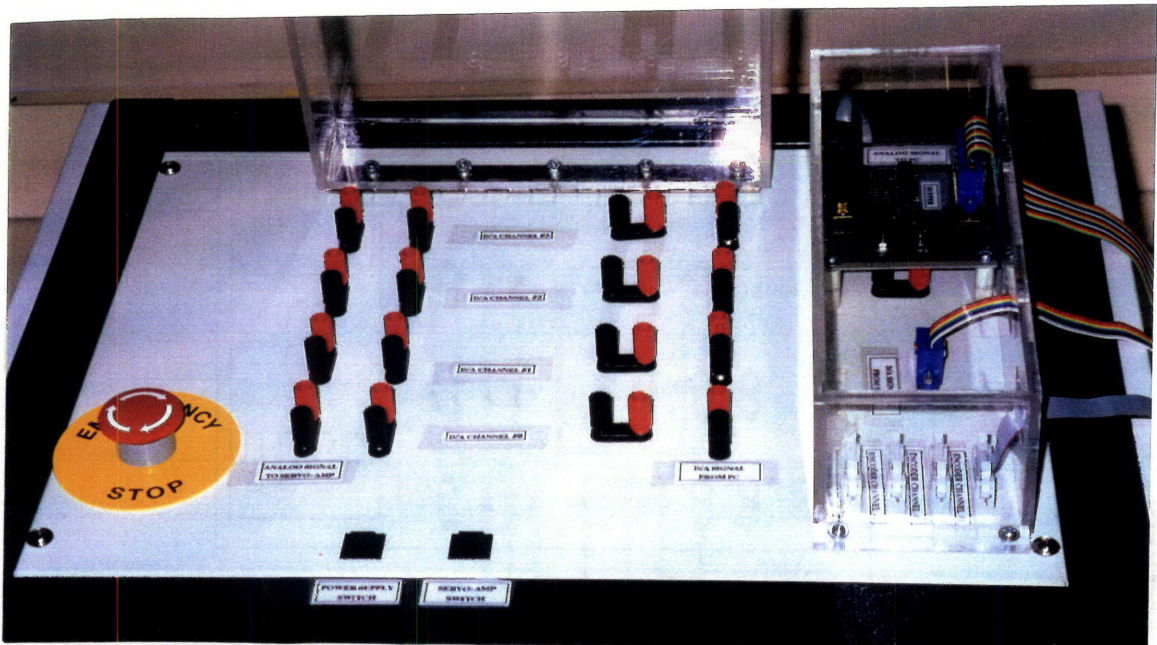
Figure 5.4: Top Panel of Electronics Module
From left to right: the "Emergency Stop" push button, the 4 rows of dual binding posts protected by a hinged Plexiglas cover, and the connections between the electronics module and the computer module covered by a Plexiglas box screwed onto the top panel.
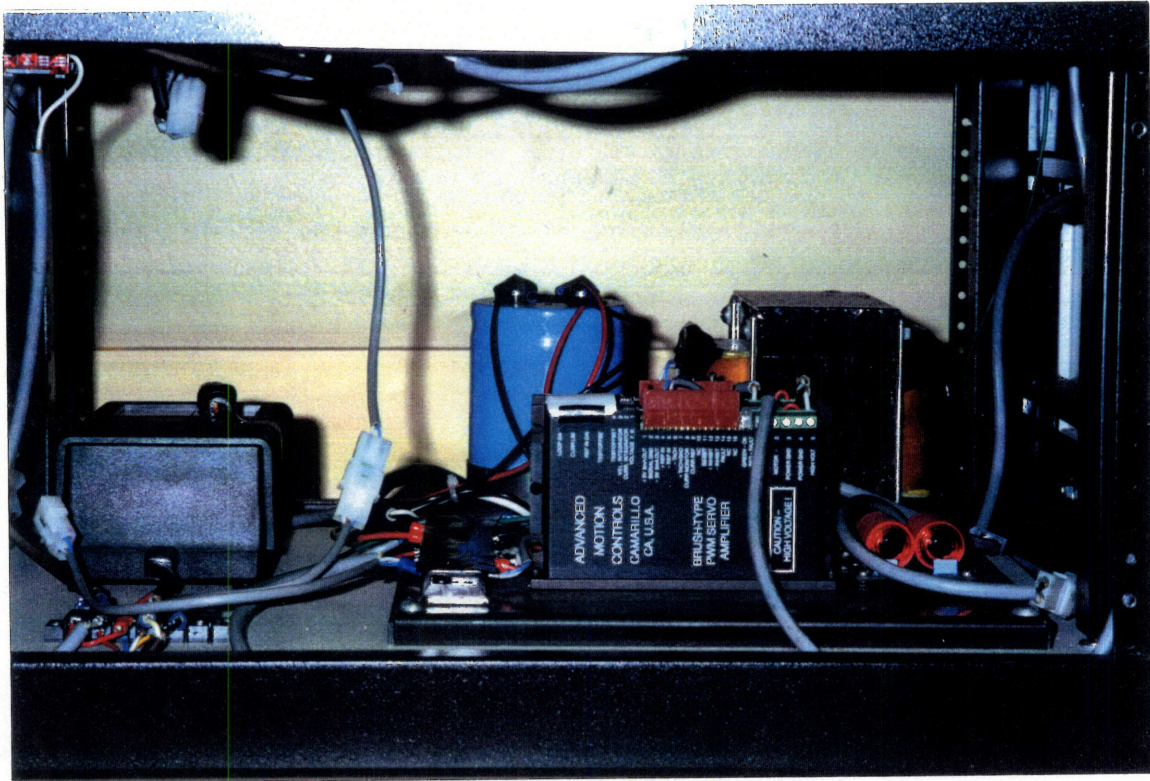
Figure 5.5: Inside of Electronics Module
*From left to right: (Back) capacitor and transformer for the servo-amplifier power
supply; (Front) ±12 V power supply, servo-amplifiers, and filter card. Some of the
connectors and screw terminals which serve to keep all panels independent are visible.*

Overall Electrical Design

Figure 5.6 represents the general schematic circuit diagram of the electronics
module taking into consideration only one servo-amplifier. Some variation of this
diagram may occur depending on which physical module is in use. For example, for the
fluids module, a filter card is required between the output of the servo-amplifier and the
input of the actuator. For the detailed pin functions of the servo-amplifier refer to the
Advance Motion Controls PWM Servo-Amplifiers Catalog [2].

Most wires used have twisted pairs and are shielded to minimize the noise intake.
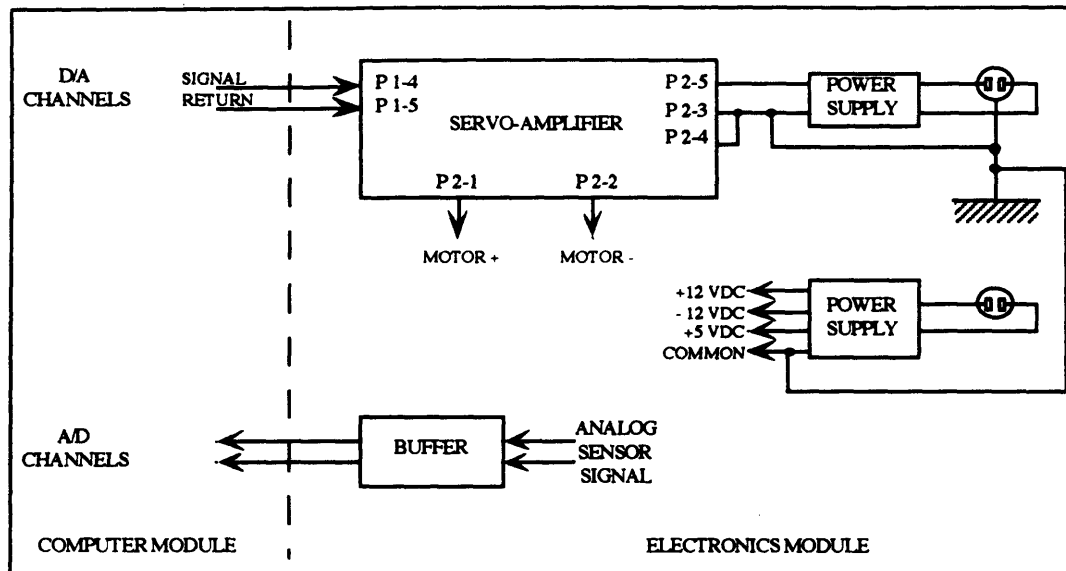
Figure 5.6: Electronics Module General Circuit Diagram

Figure 5.7 shows the circuit diagram of the unity-gain voltage follower used as a buffer on the A/D channels. As mentioned earlier, it prevents voltages outside the ±12 V range to be sent to the multifunction I/O board.
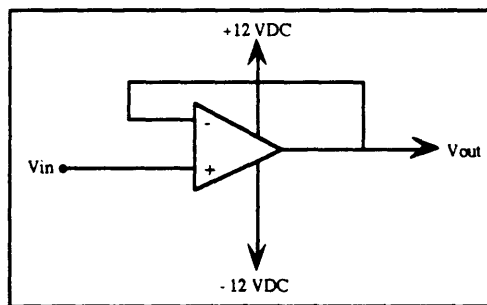
Figure 5.7: Unity-Gain Voltage Follower

Lead/Lag Compensator Analog Circuit

Electrical Circuit Design

The circuit diagram of the lead or lag and lag-lead compensators are shown respectively in Figures 5.8 and 5.9. An active circuit (with op-amps) rather than a passive one (without op-amps) was implemented. These circuits are soldered on a proto-board to ensure that students only adjust the appropriate component. However, to add some modularity to this circuit, students are given the opportunity to choose the resistance and

$$\frac{E_o(s)}{E_i(s)} = (\frac{R_4}{R_3})(\frac{R_2}{R_1})(\frac{R_1 C_1 s + 1}{R_2 C_2 s + 1})$$
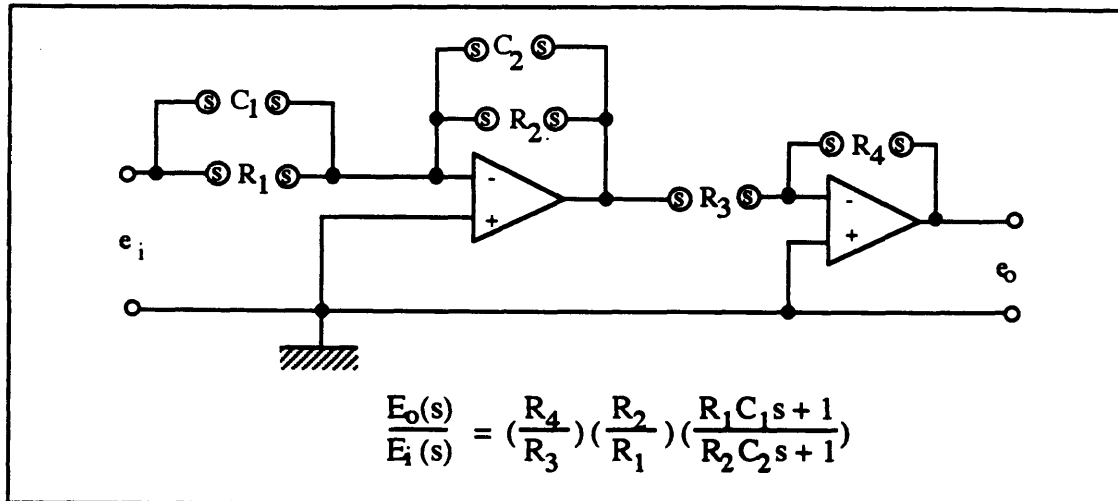
Figure 5.8: Lead or Lag Compensator Circuit Diagram

$$\frac{E_o(s)}{E_i(s)} = (\frac{R_6}{R_5})(\frac{R_4}{R_3})(\frac{[(R_1 + R_3)C_1 s + 1](R_2 C_2 s + 1)}{(R_1 C_1 s + 1)[(R_2 + R_4)C_2 s + 1]})$$
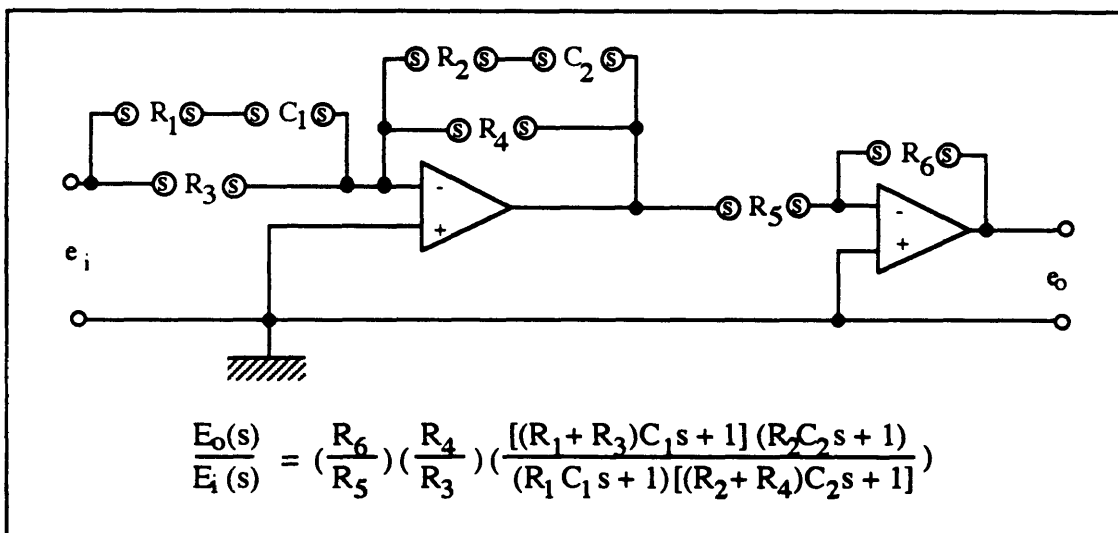
Figure 5.9: Lag-Lead Compensator Circuit Diagram

⑤ = Spring for resistor or capacitor attachement
Rs = Indicate Location of a Resistor and Resistance Value
Cs = Indicate Location of a Capacitor and Capacitance Value

capacitance value of the various resistors and capacitors. This is achieved by soldering a spring at each point where either a resistor or a capacitor should be connected. In Figures 5.8 and 5.9, those points are identified by the encircled letter "S". Using this method, students only need to wrap each leg of the resistors or capacitors to the appropriate two springs. Springs and fixed value resistors and capacitors, rather than variable resistors and variable capacitors, are used for two reasons. It keeps the cost down. It allows the students to measure the resistance and capacitance values easily.

Mechanical Design

Figure 5.10 illustrates the mechanical implementation of this circuit. On the proto-board incorporating the lead/lag compensator circuit, there are two dual binding posts representing respectively the input and output of the compensator. The input represents the D/A signal from the computer, and should be connected to the appropriate dual binding post on the right most row of Figure 5.3. The output represents the low power command signal which should be sent to the servo-amplifier, and therefore should be connected to the appropriate dual binding post on the left most row of Figure 5.3. The students will need to fit the two pairs of banana plugs located on the proto-board into the two dual binding posts located on the top panel of the electronics module and outputting respectively ±12 V, +5 V and common. Those two dual binding posts and two sets of banana plugs are oriented so that contact can be made in only one way to prevent mistakes. Banana plugs and binding post were chosen to create this contact due to their ease of use, safety, and robustness. With this design, students will just have to plug the proto-board in place, and connect four banana wires.
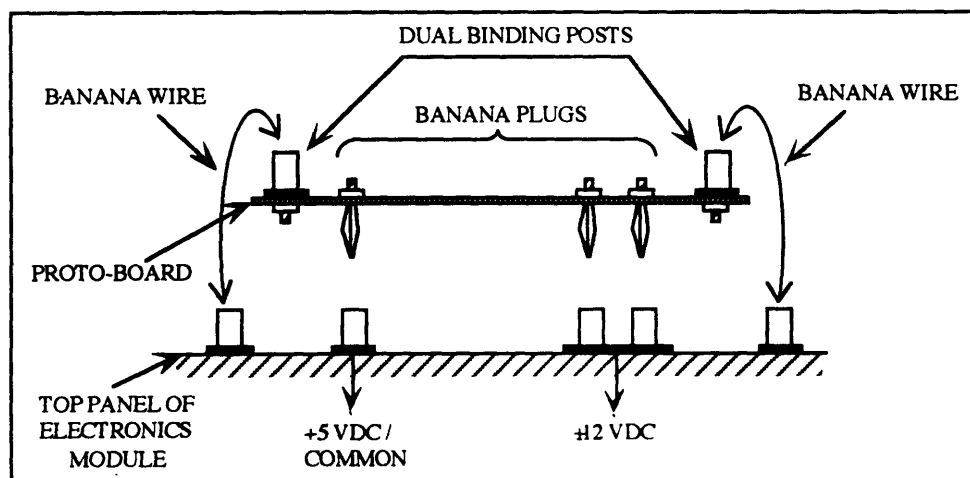
Figure 5.10: Mechanical Implementation of Analog Circuit

5.4 Interaction

The electronics module needs to interact with both the computer module and the physical module. This section discusses the means of interaction in both instances.

Computer Module

Currently three wires go between the electronics and computer modules. Two of those wires connect the multifunction I/O board to the electronics module. Those connections are made with multi-colored flat ribbon cable with male and female D-sub connectors. A 25 pin cable is used for the A/D channels, and a 9 pin cable is used for the D/A channels. Both of those wires were purchased from DigiKey.

The last wire is a 10 pin gray flat ribbon cable connecting one particular channel on the encoder board to the electronics module. This cable was purchased from US DIGITAL, the manufacturer of the encoder board used. Since the electronics module was designed to accommodate four encoder channels, if all of them are in use, there will be four such 10 pin cables between the computer and electronics modules.
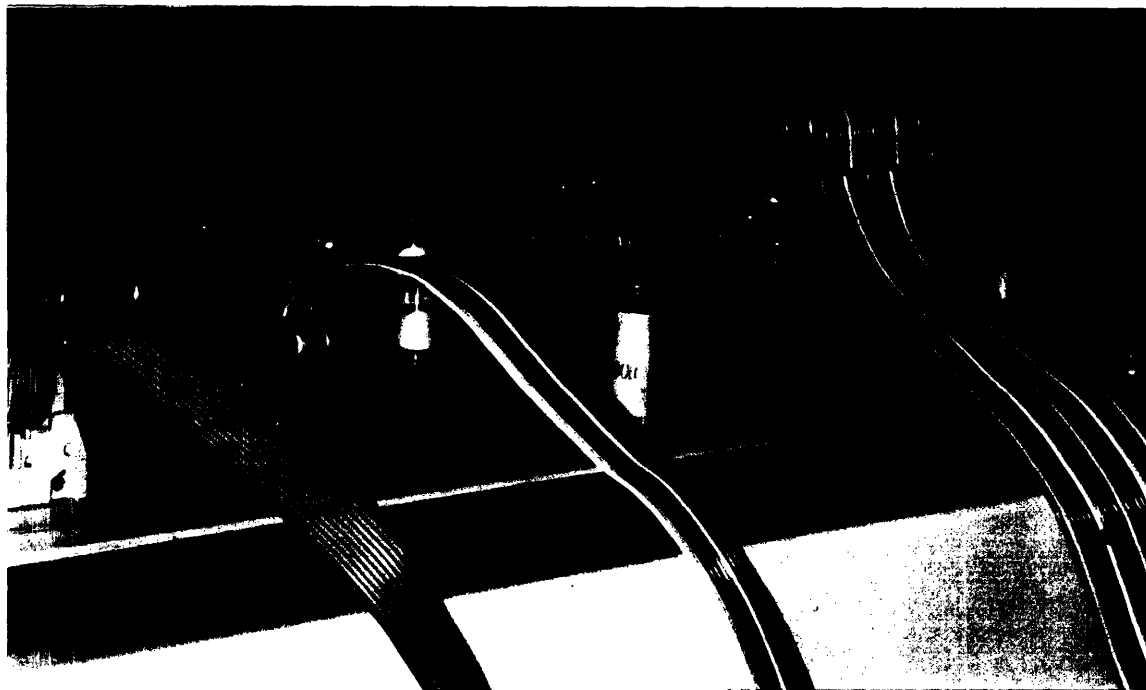
Figure 5.11: From Computer module to Electronics module

Shown are the 3 flat ribbon cables coming out of the protective Plexiglas box on the top panel of the electronics module. From left to right: 10 pin cable used for encoder signal, 9 pin cable used for D/A signal, 25 pin cable used for A/D signal.

Physical Module

For the current needs of the physical module, the connections between the physical and electronics modules are done through three wires: to the actuator, from the sensor, and an additional ±12 V power source. For modularity and consistency purposes, each connection is made using a cable having a male to male Amphenol circular connector. This implies that all the physical modules will need to carry the right size and number of Amphenol female receptacles. The left side panel of the electronics module carries seven such receptacles.

A 9 pin connector is used for the actuator signal to provide enough contacts for all four D/A channels, and an external A/D clock input connection. This connector was chosen to accept small gage wires to meet the high current requirements of actuators which might be used in the future. A 10 pin connector is used for the analog sensor signal to provide enough contacts for the 4 differential input or 8 single-ended A/D channels accounted for in the electronics module, signal ground, and an external digital trigger input connection. A 10 pin connector is used for each encoder channel. A 4 pin connector, carrying ±12 V, +5 V, and common, is used to provide an additional power source to the physical module if necessary.

Figure 5.12:   From Electronics Module to Physical Module

Shown are the 7 connectors on the side panel of the electronics module, the 3 cables which are currently used to transmit the actuator signal, the sensor signal, and the additional power supply, and the 3 connectors on the fluids module which accept these cables.

5.5 Upgradability

Two of the design objectives presented in Chapter 2 are: Open Architecture, and Modularity. This section outlines, by use of a simple example, how the design of the electronics module presented in the previous sections of this chapter meets those objectives.

For example, if one wants to control a four degree of freedom system using the equipment and software developed for the prototype System Dynamics and Controls Laboratory, one need only execute the following procedures:

Purchase additional servo-amplifiers, and mount them on the chassis of the power supply obtained from Advance Motion Controls. As mentioned in section 5.1, this power source is rated for 40 VDC at 40 Amps continuous, and therefore can supply 400 Watts to each servo-amplifier. The choice of the servo-amplifier and the necessary wiring will depend on the actuator.

Since the wiring for the D/A signal, for all four channels, has been accounted for, to control a four degree of freedom system, one will only need to connect the output of the left most row of dual binding posts to the input of the appropriate servo-amplifier (Figures 5.2 & 5.3).

The final step to ensure the flow of the D/A signal is to link the output of each servo-amplifier to the 9 pin connector on the left side panel of the electronics module which will transmit the amplified command signal to the actuator via a cable.

If an analog sensor is used, no changes will need to be made in the electronics module to take this new sensor into consideration. The cable which carries the analog sensor signal in the electronics module, the buffer, and the 25 pin flat ribbon cable providing contact between the electronics module and the computer module, are wired to accommodate 4 differential input or 8 single ended signals.

If an additional encoder is used, one will need to purchase two cables. One cable should be connected according to the encoder specifications between a 10 pin circular connector on the side panel of the electronics module, to a 10 pin straight header connector dedicated for the encoder signal, and located on the top panel of the electronics module. The other cable, a 10 pin flat ribbon cable, is to transmit that encoder signal to the appropriate encoder channel in the encoder board located in the computer module.

Though the analog control loop has been implemented only for a lead/lag compensator, it is far from being limited to this. What the electronics module provides is

the space for a proto-board of the right size to be plugged into, and the power to activate any integrated circuit on it. The actual circuit built on the proto-board will depend on the needs of the experiment, and is to be determined by the developer.

5.6 Cost Breakdown

The following table itemizes the cost of the electronics module.

ITEM & QUANTITY	MANUFACTURER & DESCRIPTION	PRICE	REF.*
Servo-Amplifier (x2)	Advance Motion Controls - Model # 25A8	$590.00	[2]
Filter Card	Advance Motion Controls - Model # FC10010	$59.00	[2]
Power Supply	Advance Motion Controls - Model # PS1200W-40V	$450.00	[2]
Power Supply	Elpac Power Systems - WM-220-1	$85.27	[36]
10 Pin Circular Connectors (x5)	Amphenol Receptacles: Model #97-3102A-18-01S Plugs: Model #97-3106A-18-01P Cable Clamps: Model #97-3057-10	$174.20	[36]
9 Pin Circular Connector	Amphenol Receptacle: Model #97-3102A-22-16S Plug: Model #97-3106A-22-16P Cable Clamp: Model #97-3057-12	$47.97	[36]
4 Pin Circular Connector	Amphenol Receptacle: Model #97-3102A-14S-02S Plug: Model #97-3106A-14S-02P Cable Clamp: Model #97-3057-6	$24.95	[36]
9 Pin D-Sub Connector	Amphenol Receptacle: Model #17D-DE9SV Plug: Model #17D-DE9PV	$9.34	[36]
25 Pin D-Sub Connector	Amphenol Receptacle: Model #17D-DB25SV Plug: Model #17D-DB25PV	$17.91	[36]
Straight Header w/ Standard Latch (x4)	Du Pont - Model #71918-110	$5.32	[36]
Luminated Switch (x2)	C&K - Model #8161J86ZQE223	$15.68	[36]
Emergency Stop Push Button	EAO Actuator: Model #704-074.2 Contact Block: Model #704-910.2 Emergency Stop Plate: Model #704-963.1	$19.64	[36]
Dual Binding Posts (x25)	H. H. Smith - Model #1810RB	$142.00	[36]
Banana Plugs (x18)	H. H. Smith - Model #102	$25.38	[36]

* Indicates vendors.

Prototyping Board (x2)	Vector Electronic Company - Model #8006	$76.44	[36]
Single Op-Amps (x8)	Analog Devices - Model #OP07CP	$14.48	[36]
Quad Op-Amps (x2)	Analog Devices - Model #OP497GP	$15.88	[36]
Cabinet	Zero Stantron Frame: Model #IC5002508 Top & Bottom Panels: Model #P14 Front Panel: Model #P8 Side Panels: Model #SSIC5002508	$213.80	[50]
Miscellaneous	Cables, Heat Shrink, Spacers, Lugs, Standoffs ...	$250.00	
	TOTAL COST:	$2,237.26*	

Table 5.3: Cost Breakdown of the Electronics Module

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* All the items purchased from [36] include a special MIT discount. Total does not take into consideration the cost of shipping and handling, machining, and assembly time.

CHAPTER 6

FLUIDS MODULE

The heart of the Systems Dynamics and Controls Laboratory is the physical set-up. As mentioned in Chapter 2, one of the design objectives for the prototype is to provide the laboratory with a modular structure for the integration of interdisciplinary set-ups. The previous two chapters covered the applications and properties of the computer module and the electronics module which serve as the means of achieving a modular structure. To demonstrate the practicality of the three module design, and to illustrate the possible interdisciplinary nature of the laboratory, two physical set-ups representing two different fields of Mechanical Engineering were built.

This chapter concentrates on the water level control system, one of the two physical set-ups in the prototype laboratory, which has been designed and built by German Soto and myself. First, the design options are evaluated, and a general design concept is outlined. A simulation-based feasibility analysis is presented, followed by the final design dimensions and hardware selection. Then, the procedures necessary to ensure the compatibility between the three modules (computer, electronics, physical) are described. Some of the discrepancies between the experimental and simulation results are explained. An evaluation of the design presented in this chapter is also given. Finally, the required maintenance procedures are outlined.

6.1 Design Options
The features sought in the design of the fluids system are listed below:
- A physical set-up which allows for three different configurations: one tank, two tanks in parallel, and two tanks in series to represent first order, second order coupled, and second order decoupled systems, respectively.
- A system that can be modeled accurately by students with only an introductory background in system dynamics.
- A system where some plant parameters can be changed easily.

- A system which could lead to interesting experiments, and introduce students to some more advanced topics in control theory.

- A system without too many tanks, tubes, and wires, so as not to confuse students.

Designs Proposed at Other Schools

As mentioned in section 2.2, from the literature reviewed, many of the schools renovating or creating control systems laboratories are building fluids systems for the students to work on. The proposed designs of the fluids systems are as numerous as the papers describing them. Therefore, each design was evaluated against the intellectual requirements of the prototype System Dynamics and Controls Laboratory listed in Chapter 2, and a few are presented below. Recall the key intellectual requirements identified in Chapter 2: Modeling/System Identification, Simulation, Dynamics Behaviors, Feedback and Control, Controller Design, Introduction to Discrete Time, and Advanced Topics in Controls.

At Texas A&M University, the fluids system was supplied by TechQuipment. It consists of a container divided in two by a perforated partition. There are four holes of different sizes in this partition which can be plugged or unplugged to change the level of interaction. When all four holes are unplugged, the container can be considered as one big tank [33]. With this design, two configurations are possible: one tank or two tanks in parallel (coupled tanks). Students are not given the possibility to work on a system where there is no interaction between the two tanks (decoupled tanks). Since several holes of different sizes are available, and the outlet of the second tank is an adjustable tap, the dynamic behavior of the system can be observed. However, the way the interaction between the two tanks is altered is not practical, especially when changes need to be done during an experiment.

In another report from Texas A&M University, a coupled water tanks experiment which includes two pumps is briefly described [21]. Since the prototype laboratory at MIT focuses on introductory undergraduate education in the area of system dynamics and controls, and at this level students are not introduced to more than one degree-of-freedom systems, such an experiment would not be appropriate.

The fluids system developed at Bucknell University exposes the students only to a first order system (one tank). An additional drawback to this design is that none of the plant parameters can be adjusted. Therefore, students are able to study the dynamic behavior of the system for only a given set of specifications.

At California State Polytechnic University, Pomona, the fluids systems represents a liquid-level and flow simulator. This system is the most complex of all the systems

presented above, and meets all the intellectual requirements of the prototype laboratory at MIT. It includes two tanks, three water columns with adjustable heights, and a number of needle valves, control valves, pressures relief valves, and solenoid valves. This apparatus provides for several configurations which result in systems from first to third order with or without pure delay. Due to the location of the tanks, water can flow either by gravity or by pump flow in the water columns [22].

New Design Concept

None of the experiments presented above were selected because they were either too complex (two actuators) or much too simple, and therefore did not meet all of the intellectual requirements of the prototype laboratory. Furthermore, many experiments were either too difficult to manufacture or not sufficiently modular. As a consequence, a new design concept, illustrated in Figure 6.1, was proposed.
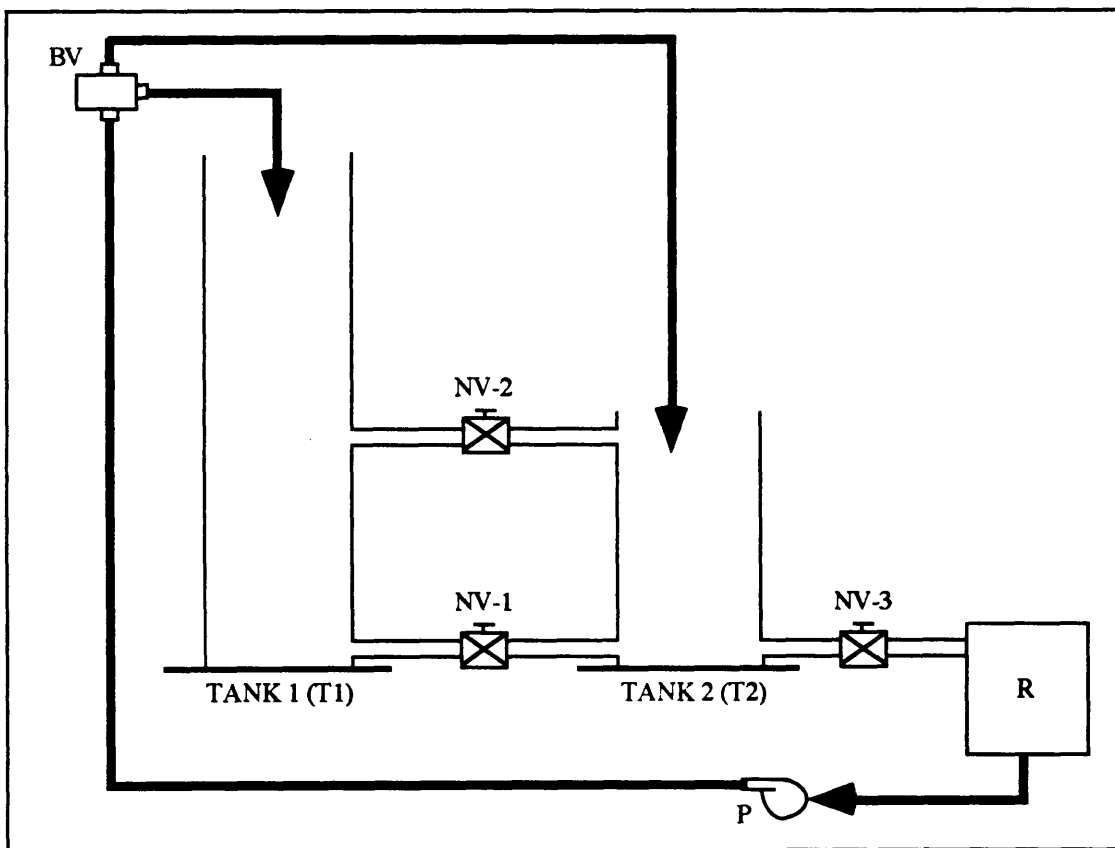

Figure 6.1: Schematic Drawing of the Water Level Control System

This set-up includes a reservoir (R), a pump (P), two tanks where Tank 1 (T1) is twice the length of Tank 2 (T2), and valves. The three valves (NV-1 to NV-3) are needle valves and therefore permit the resistance of the valve to be changed continuously from fully open to fully closed. The outlet of the pump is bifurcated, using a 3-way ball valve (BV), to either the top of Tank 1 or Tank 2. The arrows in Figure 6.1 represent the water flow.

To study control concepts on a first order system, only one tank needs to be used. To implement this system, the water inlet must be directed to the top of T2 by adjusting BV. Moreover, NV-1 and NV-2 must be fully closed while NV-3 is kept open.

To study control concepts on a second order system, two tanks need to be used. The two tanks can be either coupled or decoupled. In both cases, the water inlet must be directed to the top of T1 by adjusting BV. For the coupled tanks configuration the tanks are placed in parallel, and the water can flow freely from one tank to the other. This configuration is achieved when NV-1 and NV-3 are open while NV-2 is fully closed. For the decoupled tanks configuration the tanks are placed in series. This implies that the water can flow in only one direction: from T1 to T2. This configuration is achieved when NV-2 and NV-3 are open while NV-1 is fully closed.

For all three configurations, the goal is to control the water level in Tank 2 by controlling the flow rate of the pump. The water level in Tank 2 is sensed using a pressure transducer located at the bottom of the tank.

With this design concept, all the features sought in the hardware, and listed earlier in this section, are realized. The hardware enables students to work on three different configurations by simply adjusting three needle valves. For each configuration, the plant parameters can be changed by adjusting the appropriate needle valves, thus allowing for a more thorough study of the dynamic behavior of each configuration. The linearized equations required to obtain the transfer function for each plant configuration are straight forward and often used as examples in system dynamics courses (Appendix G).

6.2 Feasibility Study

To be able to build a working system satisfying this general design description, one needs to obtain more specific information on the power of the pump, and the dimensions of the tanks, the connecting tubes, and the reservoir. Thus, a feasibility analysis must be pursued to identify a set of hardware specifications that will make the experiments both practical to implement and interesting for the students.

This section gives a definition of a "good experiment", and presents the theoretical work done which led to the specific hardware selection.

Good Experiments

Both Astron and Auslander list some of the attributes of a good laboratory experiment [4, 5]. The ones that are mainly taken into consideration in this section are related to the time scale of the experiment and its visualization. 1) It is important that the time scale of the physical apparatus be slow enough so that the students can see what is happening, but not so slow that it is boring. 2) To make the experiment more visually interesting, the system response should be of a relatively large magnitude. For example, in the water level control system, students should be able to input steps of more than 10 inches. If the step size and percent overshoot are kept small, not only will the students not be able to distinguish it, but the accuracy of the sensor will have to be greater, and the actuator will also need to be much more responsive to small variations. 3) Another visual consideration is the amount of splashing that will occur when transferring water. The splashing will impair student's ability to measure an accurate water level, and will affect the sensor reading. To avoid an excessive amount of splashing, the water flow should be kept in the laminar flow or the low turbulent flow region.

To design a physical system which is able to meet these criteria, the following steps were taken for all three configurations of the water level control system. First, linearized equations of the three systems, as well as their plant transfer functions in the s-domain, were obtained (Appendix G). Second, simulations were run using the ideal plant transfer function, and repeated with varying values of the valve resistances and cross sectional area of the tanks. Those values were chosen keeping in mind that the smaller the tank cross sectional area the faster it will get filled, and the larger the amplitude of the response will be.

Simulations

Simulations were carried out using the MATLAB/SIMULINK software package. The goal of running simulations was to identify the cross-sectional area (C) and height for the two tanks, a resistance value, and the maximum flow rate at which the pump will have to operate. The resistance value (R) then directly determines the diameter of the outlet hole. One restriction, which was imposed while running the simulations on SIMULINK, was on the range of flow rates the pump could output. Obviously, to make the simulation realistic, the flow rate cannot be negative, since negative values would mean that the water would be sucked out of the tanks, and the design does not allow for that. Appendix H includes sample simulation results for first order and second order coupled systems, along with the SIMULINK block diagrams used.

Two variables need to be observed in the simulation results. First, the maximum height the water reaches should not be excessive. This experiment is meant to sit on a table top, and students should not have to lift their heads too much to see the water level. Second, to avoid as many nonlinearities as possible, saturation of the pump input voltage should be kept to a minimum. Saturation may occur due to the constraint imposed on the range of output flow rates for the pump.

For the first order system, the open loop time constant is the product of the resistance and the capacitance ($\tau = RC$). To obtain a system that is not too slow, this time constant was kept around 30 seconds.

Hardware Specifications

Following the above constraints and recommendations, the simulations were repeated many times, while iterating the resistance and capacitance values, to obtain the following hardware specifications (Figure 6.2):

Inner diameter of Tanks 1 & 2 (D1 & D2) = 1 inch.

Length of Tank 1 (L1) = 48 inches.

Length of Tank 2 (L2) = 24 inches.

Inner diameter of outlets of Tank 1 and inlets of Tank 2 (d1 & d2) = 0.25 inches.

Inner diameter of outlet of Tank 2 (d3) = 0.25 inches.

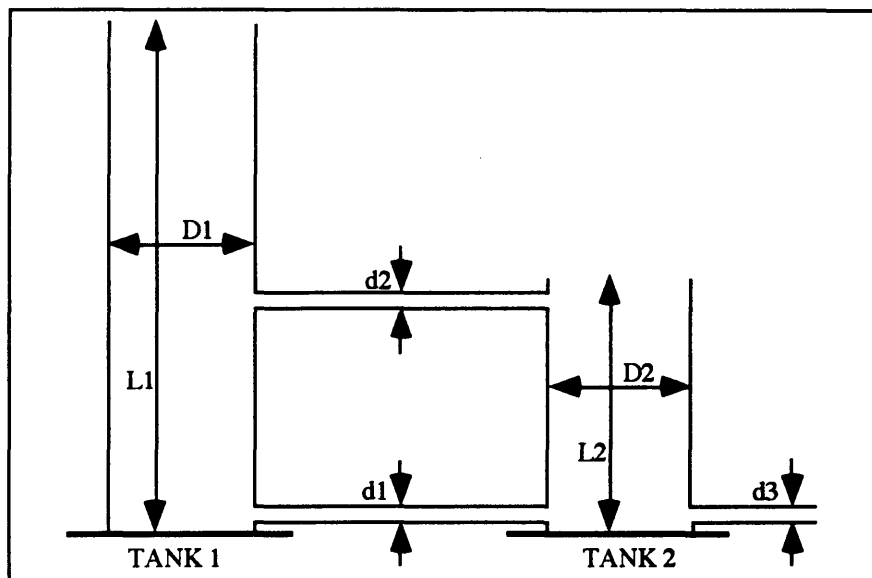Flow rate of the pump does not exceed 5 gallons-per-minute (GPM).

Figure 6.2: Dimensional Schematic Drawing of the Water Level Control System

With these dimensions, the plant satisfies the time scale and visibility criteria for a "good experiment."

6.3 - Hardware Selection

Two generations of the prototype water level control system were built. The purpose of the first generation system was to validate the simulation results, demonstrate the feasibility of the design, and troubleshoot any problems. This system was not meant to be used by anyone other than the developers, and therefore did not need to be overly robust or aesthetically pleasing. Moreover, this system was built with a very low budget (less than $500.00, of which $322.50 were covered by donations from March Manufacturing, Inc. and Omega Engineering, Inc.). Once the system proved to be an educationally valuable and interesting experiment, a second generation water level control system was designed, fabricated, and assembled by German Soto [45] and myself.

The design concept of the second generation fluids module is the same as the first generation one. All the dimensions specified in section 6.2 are valid for both systems. The actuator and sensor are the same for both systems. However, one should refer to [45] for the assembly drawings, detailed part designs, as well as the cost breakdown of the second generation fluids module.

This section concentrates on describing the major hardware components selected for the water level control system. Those are the pump, the pressure sensor, and the tank and tubing material.

Pump

Two factors are necessary to choose a pump: flow rate and head. From the simulations performed, we know the flow rate should not exceed 5 GPM. The total head for the second generation system was estimated at 10 ft using Bernoulli's equation and the expression for the frictional and minor losses [35].

Since the objective of the experiments is to vary the flow rate, and therefore the speed of the pump, in a continuous fashion according to the feedback from the pressure sensor, a DC powered pump was necessary. Other criteria for the selection of any item are the size and the cost.

Given those parameters, the centrifugal pump model #809-BR-HS-12 from March Manufacturing, Inc. was selected. The pump specifications are: 12 VDC, maximum speed of 3600 RPM, maximum head of 15.5 ft, and maximum flow rate of 7.5 GPM [28]. This pump, which costs $256.00, was donated by March Manufacturing, Inc.

Both the electrical and mechanical time constants are on the order of a few

milliseconds, and therefore the dynamics of the pump do not need to be taken into consideration in the overall system, since the time constant of the fluids system is much longer.

Because the performance of a centrifugal pump is dependent on the pressure differential across the pump head, differences in the water level in the reservoir during the experiment affect the performance. To minimize this problem, the dimensions of the reservoir must serve to optimize the cross-sectional area.

Pressure Sensor

Since the pressure sensor is located at the bottom of Tank 2, and the length of Tank 2 is two feet, the water column height that the transducer needs to sense varies from 0 to 24 inches. Therefore, for this system, a low pressure transducer is needed. Moreover, since the tank inside diameter is one inch, the sensor needs to be compact. The output of the sensor should be in volts to be compatible with the input of the A/D channels of the multifunction I/O board.

The pressure transducer and the electrical connector selected were donated, and are manufactured, by Omega Engineering, Inc. These items are respectively model #PX170-28GV and model #CX-136-4, and total $66.50. The working range of the selected gage type pressure transducer is 0 to 28 inches of water. It requires an excitation of 10 VDC at 2 mA, and outputs at 28 inches 42 ±2 mV with an accuracy of ±1.5% of the full scale output (FSO) and a repeatability of ±0.25% FSO. This sensor is subcompact, measuring 0.85 x 0.85 inches [38]. The response time of the sensor is on the order of one millisecond, and therefore is appropriate for use in continuous time control.

Tank and Tubing Material

The material used for the tanks is clear Plexiglas. It allows the student to easily see the water level, and therefore enhances the visualization of the system response. Most of the tubing used in the second generation design is clear and rigid. Moreover, all the valves, connectors, and tubing support are commercial products [45].

All the components which need to be easily accessible or visible to the students are located above the workbench and mounted on an aluminum base plate. Components which do not need to be accessed by the students are located underneath the tabletop to save space (see Figure 6.3).
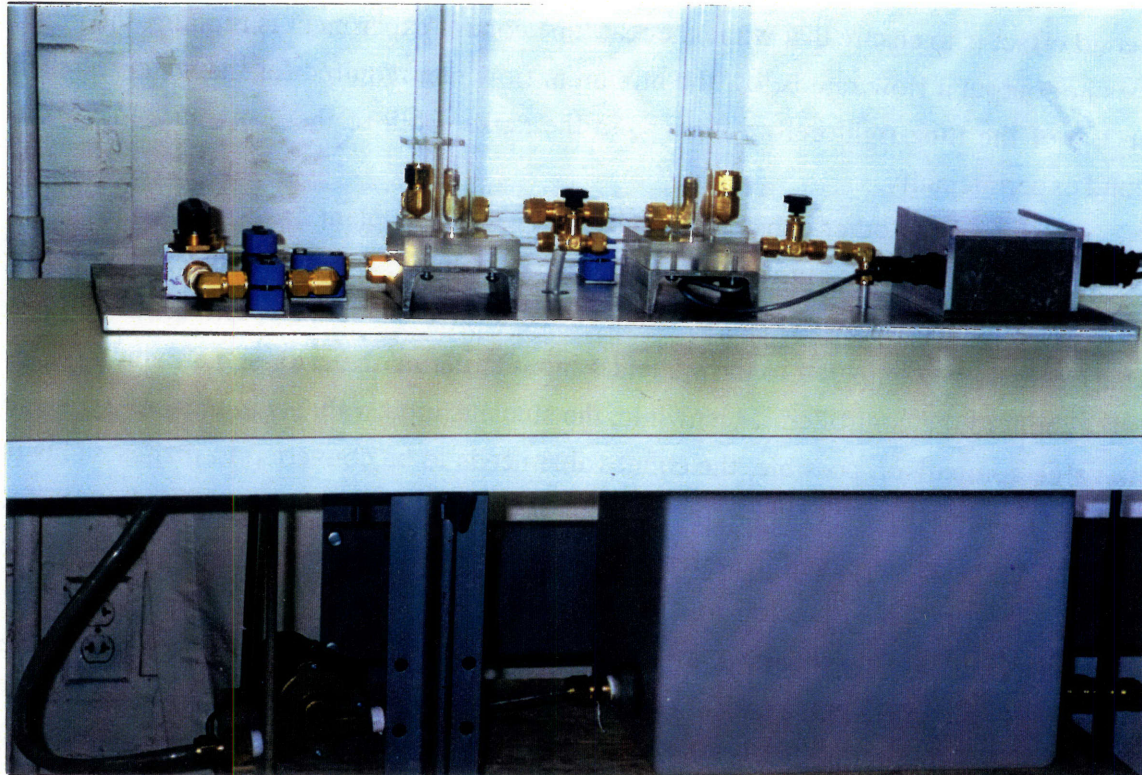
Figure 6.3: Close-Up of Fluids Module
Above the workbench from left to right: 3-way valve, Tank 1, needle valve NV-1, Tank 2 with pressure sensor mounted underneath, needle valve NV-3, and electronics box for electrical connections and sensor conditioning. Below the workbench from left to right: pump, reservoir.

6.4 - Compatibility Between Modules

Though the computer and the electronics modules have been developed so as to support a variety of physical modules, some tailoring must be done for each specific plant. Minor adjustments must be made to the software in the computer module, to the servo-amplifier in the electronics module, and to the sensor signal in the physical module. This section covers those three modifications.

Computer Module

Real-Time Control Software

The computer module implements the real-time control algorithm and outputs the voltage required to control the pump flow rate via the multifunction I/O board. Due to the nonlinear nature of the fluids system, several constants and offsets are needed to match the control algorithm to the specifics of the plant.

To avoid having delays while running the experiments, two offsets are defined. The first one occurs before the start the experiment and ensures that the pump is running fast enough so that water is flowing in the tubes and falling in the appropriate tank. The

second offset is to ensure that while the real-time control experiment is running, the pump does not output a flow rate below the minimum flow rate required for the water to reach the top of the tube right before it drops in the tank. Both of these offset values were found experimentally.

Some of the other constants required for the fluids plant are conversion factors. For example, the sensor outputs an analog signal (voltage) which, when read by one of the A/D channels on the I/O board, is converted to discrete counts. The count value is what needs to be compared to the student's input to define the error signal which serves as the input to the controller. Meanwhile, the students input value is in inches. To make the value comparison possible, the count value needs to be converted to inches. This is done by multiplying the count value by a factor which converts counts back to voltage, and then by using an equation which relates inches of water to voltage output from the pressure sensor. This equation was determined experimentally (Appendix J). Another conversion factor is also necessary to relate the voltage output by the I/O board with the water level (in inches) in the tank.

For more information on the implementation of the offsets and conversion factors, refer to J. Hintersteiner's thesis [19].

Graphical User Interface

As mentioned in section 4.3, although the structure of the GUI is kept the same for all the physical modules, the content differs and needs to be tailored to the specific experiments performed on a particular physical plant. See R. Wang's thesis [48] for details.

Electronics Module

The actuator being used for the water level control system is a centrifugal pump. Thus, as explained in section 5.1, the voltage of the pump needs to be controlled since there is a linear relationship between the voltage, the speed, and the flow rate. Therefore, a voltage-to-voltage servo-amplifier is needed to scale up the output voltage of the I/O board to the required input voltage of the pump, and this servo-amplifier needs to be calibrated. The calibration procedure is outlined below.

Using the motor without the load, and setting the servo-amplifier in the test mode using the DIP switch, the loop gain and offset potentiometer should be set. The current limit and reference gain potentiometers are set while the load is attached to the motor, and the DIP switch is set to voltage mode. The current limit ensures that the instantaneous motor current does not exceed the specified motor peak current rating. It therefore serves

as a safety measure to limit the voltage output of the servo-amplifier. The reference gain needs to be set to the appropriate gain by adjusting the potentiometer while comparing the input voltage to the servo-amplifier and the output voltage from the servo-amplifier. As an added safety measure, the voltage-to-voltage servo-amplifier is inhibited so as to prevent any negative voltage from going to the pump. As discussed in section 5.1, a filter card is added between the output of the servo-amplifier and the input to the actuator to prevent commutator problems by increasing the inductance of the system.

The maximum voltage output range of the D/A channels on the I/O board is -5 V to +4.9976 V. The pump data sheets show performance curves for voltages up to +14 VDC, though it is rated for 12 VDC. Therefore, a gain of 2.6 was chosen so that the output range of the multifunction I/O board corresponds to the operating range of the pump (0 to +13 VDC). A sample calibration of the March Manufacturing, Inc. pump is show in Appendix I. More information on the calibration procedure can be obtained from the Set-Up Instructions & Application Notes section of the *Advance Motion Controls PWM Servo-Amplifiers Catalog* [2].

Physical Module

The last step that needs to be performed to ensure complete compatibility between the three modules is conditioning of the excitation and output sensor signals.

Excitation of Sensor

The excitation to the pressure sensor is provided by a signal conditioning circuit activated by the ±12 VDC power supply located in the electronics module. This signal conditioning circuit, by means of an inverting amplifier, serves to transform the -12 VDC input to +10 VDC output which is required for the pressure sensor excitation (Figure 6.4).
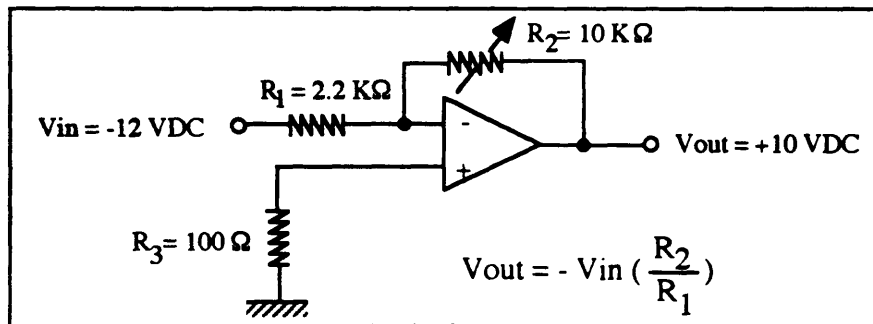

$$Vout = - Vin \left(\frac{R_2}{R_1} \right)$$

Figure 6.4: Pressure Sensor Excitation Signal Conditioning

Output Sensor Signal

As mentioned in section 6.3, the output range of the pressure sensor is on the order of millivolts. The I/O board on the other hand is a 12 bit board whose resolution is not high enough to distinguish such low voltage values. Therefore, the output sensor signal needs to be amplified before it is read by the A/D channels on the I/O board.

This amplification can be done by the on-board programmable gain amplifier (PGA). The drawback to using the PGA is that the amplification will be applied to all channels. This means that some channels which did not need to be amplified would have too high of a voltage, and would burn the A/D channel, unless their voltage is attenuated. The I/O board also provides for an on-board circuit pad. This circuit pad accepts user-installed shunt regulators, attenuators, and filters, but does not provide for amplifications. If a signal were to be amplified using the I/O board, it would have to be done using the PGA, while for the channels with a high voltage not requiring amplification, an attenuation would need to be applied using the on-board circuit pad. This option is simply not practical. Moreover, having to amplify all channels and attenuate only certain ones will lead to more errors than just tampering with the one channel that needs amplification or attenuation. For these reasons, as well as the consideration of noise intake affecting low power signal (see section 5.3), the output sensor signal, like the sensor excitation, is conditioned at the level of the physical module.

Given the full scale output range of the pressure sensor (0 to 42 mV) and input range of the I/O board (±5 V), the amplification used is a gain of approximately 100. Figure 6.5 represents the circuit diagram of the output sensor signal conditioning. Appendix J includes the graph of a typical Pressure Sensor Output Voltage vs. Tank Water Level graph.

The amplification of the output sensor signal, like the excitation of the sensor, is activated by the ±12 VDC power supply located in the electronics module.

Electronics Box

The circuits for the sensor excitation and output signal amplification are located in the electronics box of the physical module. This box is mounted on the base plate of the physical module, and serves to group all the electrical connections in one area. It contains all the necessary Amphenol female circular connectors to accept the male-to-male cables connecting the electronics module to the physical module. Moreover, additional connectors provide links to the pressure sensor and the pump (Figure 6.6).
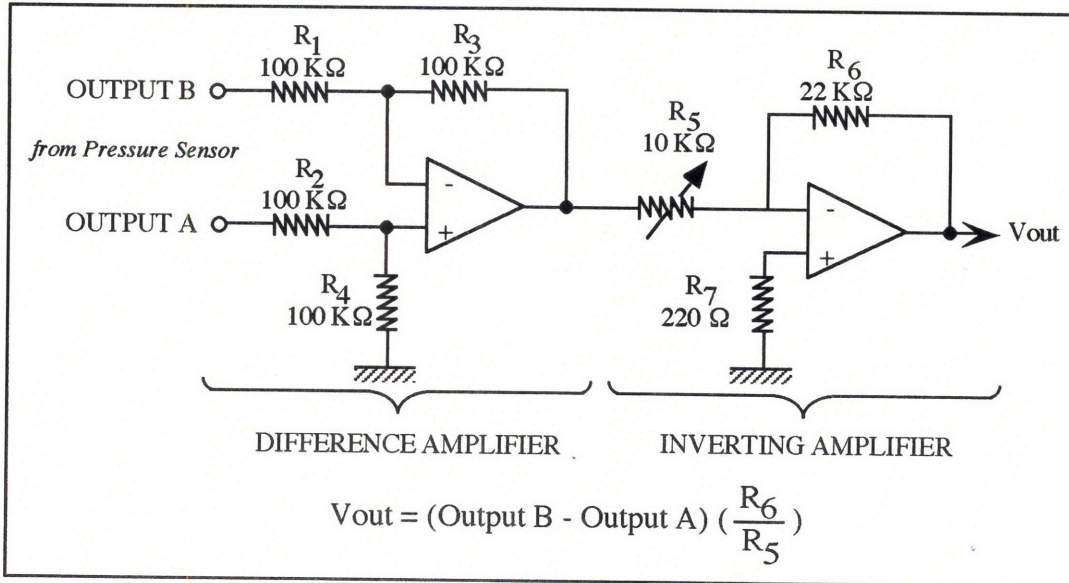
Figure 6.5: Signal Amplification of Output Sensor Signal
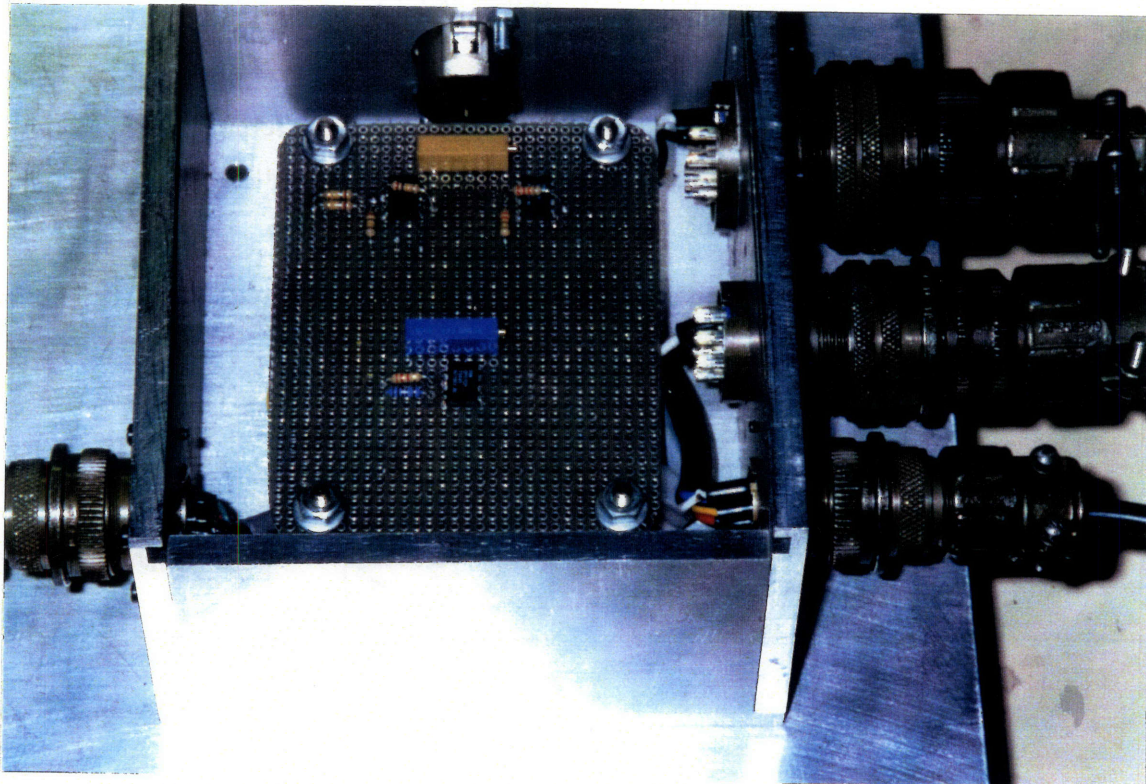
Figure 6.6: Electronics Box of the Fluids Module

Left: 4 pin connector carrying sensor excitation and output signals to and from sensor. Back: microphone connector carrying signal to pump. Right, from top to bottom: 9 pin connector for actuator signal, 10 pin connector for sensor signal, 4 pin connector for additional ±12 VDC power supply. Connectors on the right side of the electronics box carry signals to and from the electronics module. Inside: proto-board with sensor output signal amplification (top) and sensor excitation (bottom).

6.5 Discrepancies Between Simulation and Experimental Results

So far this chapter has introduced the preliminary design and calibration work necessary to ensure proper operation of the equipment. Now, the effects of reality on the system response while running real-time control experiments are discussed. Some simulation and experimental results can be found in Appendix H.

The figures in Appendix H show that the experimental and simulations curves are reasonably consistent. Moreover, as the controller gains get larger, the discrepancies between the simulation and experimental results diminish. Those discrepancies are mainly due to the nonlinearities inherent in the system and are most obvious for low gains (Figure H.3).

The water level control system has two major nonlinearities. First, the water level cannot go below zero. As illustrated in Figure 6.7, where an oscillatory response for a given step is represented, the response would ideally go to negative heights but it is chopped at zero. This means that the error value will not be large enough to trigger the controller to increase the flow rate in a reasonable amount of time. Second, the water cannot be sucked out of the tanks. This is due to the fact that a centrifugal pump cannot operate in reverse direction, and that the design does not allow for water which has dropped in the tank to be sucked back up. Figure 6.8 shows the difference between the flow rate curves for the ideal and real cases. In the former, negative flow rates are acceptable. In the latter, the values do not go negative.
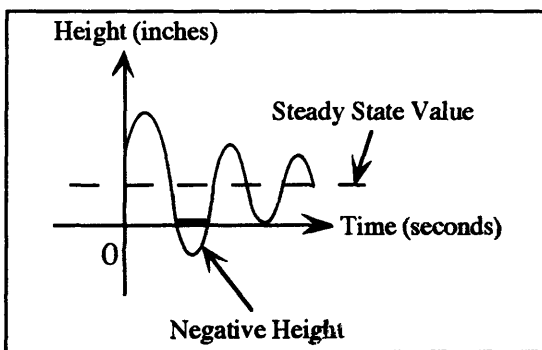

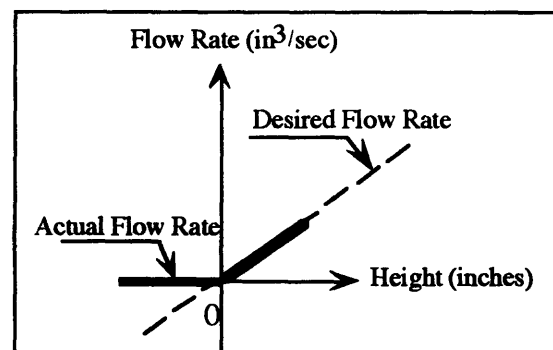Figure 6.7: Height Constraint   Figure 6.8: Flow Rate Constraint

6.6 Evaluation of Fluids Module Design

This section concentrates on the evaluation of the pump. For specific comments on the hardware design refer to German Soto's thesis [45].

The centrifugal pump selected for the actuator does not give consistent results.

Most importantly, when the input to the pump is a constant voltage, the water level in the tank varies with time. Oscillations of ±1.5 inches were observed under typical conditions. According to the pump manufacturer, this might be due to the fact that the impeller has a large clearance. With a large clearance, the pump is easier to manufacture and assemble, and therefore cheaper, but it is not designed to be used when precise measurements are required. This pump is designed for closed loop systems or for transfer of water when the precise flow rate is not monitored and is not a major concern. A fixed displacement pump should eliminate those problems. For the second generation water level control system, such a pump was selected. However, it did not become part of the final design because, when put to use, the pump needed a high initial voltage due to its high current requirement, which needed to be lowered very soon following the kick off to prevent overflow. Though it is clear that the March Manufacturing, Inc. centrifugal pump has to be replaced by a fixed displacement pump, the current specification of this fixed displacement pump has not been determined.

6.7 Maintenance

The calibration of three items needs to be performed or checked on a regular basis: servo-amplifier, sensor excitation, and sensor output amplification gain. Recalibration is necessary from time to time because all these components are made of electronics parts, which tend to drift over time.

Drainage of the water should be done on a regular basis to avoid large particles of dirt from flowing in the system and getting trapped in the pump or valves.

CHAPTER 7

STUDENT TESTING

Once the physical hardware was built and assembled, the real-time control software was written and debugged, and the system as a whole was working properly, an evaluation of the package was done. The objective of this evaluation was to test whether the prototype system has met its goals in terms of the intellectual requirements and the educational issues presented in Chapter 2.

This chapter covers the procedure by which the evaluation was acquired, and presents the results.

7.1 Procedure

The best way to test whether the prototype system has met its goals is to invite students to use the prototype system and give feedback. The benefits of this student testing are twofold. First, the feedback obtained comes from the end-user. Second, the feedback helps the developers focus their efforts on areas that need improvements.

This section covers the preparatory work involved, the students recruited, and the test method.

<u>Preparatory Work</u>

To make the evaluation more meaningful, it was decided that the students should work in an environment that reflects as much as possible the situation students attending a laboratory face. Therefore, pre-laboratory homeworks and laboratory handouts were compiled. To make the experience more valuable, three sets of homeworks and handouts were written for each physical module. The combination of all this laboratory material covers most of the control concepts included in the intellectual requirements. In conjunction with each handout and homework, the graphical user interface and the Word document for report write ups were developed. Appendix K includes a sample homework and handout written for the fluids system along with a complete answer key. Refer to R. Wang's thesis [48] for a sample pre-laboratory homework and laboratory handout on the

electromechanical module.

The work so far presented in this thesis represents the building blocks for this preparatory work which puts into practice the interaction between the prototype system and the end-user. With this preparatory work completed, students are given the chance to compare the means of experiencing the same control concepts between the prototype laboratory and the current Control Systems Laboratory.

Students Recruited

To obtain a more solid comparison between the old and prototype laboratories the students performing the testing need to be familiar with the current method of education and with control concepts. Therefore, the students recruited to perform the testing are students either currently taking 2.14 and attending the laboratory, or students who have attended this class recently.

A total of 11 students volunteered to evaluate the prototype System Dynamics and Controls Laboratory. Five of them performed the experiments on the water level control system, and six on the linear slide table system. All the students were enrolled in 2.14 at the time of the testing. Of those 11 students, 9 were undergraduates in the Mechanical Engineering Department, one was an undergraduate with a double major in mechanical engineering and mathematics, and one was a graduate student in the Mechanical Engineering Department. Among the undergraduates, 4 were seniors, and 6 were juniors.

Test Method

To ensure a proper evaluation of the prototype system, some standard evaluation method needed to be implemented. A survey (Appendix L) was written to serve this purpose. The survey contains general quantitative questions which asks the students to rate the prototype laboratory compared to the old one on a scale from 1 to 10 where 1 is "worse than old laboratory" and 10 is "better than old laboratory". This survey also contains qualitative questions which help the developers evaluate how comfortable the students feel in this new working environment. Finally, the survey asks more specific questions on the validity of several components such as the graphical user interface.

The volunteers were placed in groups of two, at the most, to perform the experiments. This agrees with the proposed laboratory environment presented in section 3.6.

Each group was asked to go through at least one complete laboratory session.

7.2 - Results

Evaluation of Prototype System

For ease of use, overall experiment, and educational value of the prototype system compared to the current laboratory, the students rated on average 8.7, 8.7, and 9.1 out of 10 respectively (Figures 7.1 - 7.3). The ease of use refers to the interface between the student and the three modules (computer, electronics, and physical). The overall experiment refers to the interest level while performing the experiments. The educational value refers to the clarity of the concepts illustrated. To evaluate those three areas in more detail, students were asked to provide narrative comments on the simulations, the graphical user interface, and the equipment (electronics module and physical module).
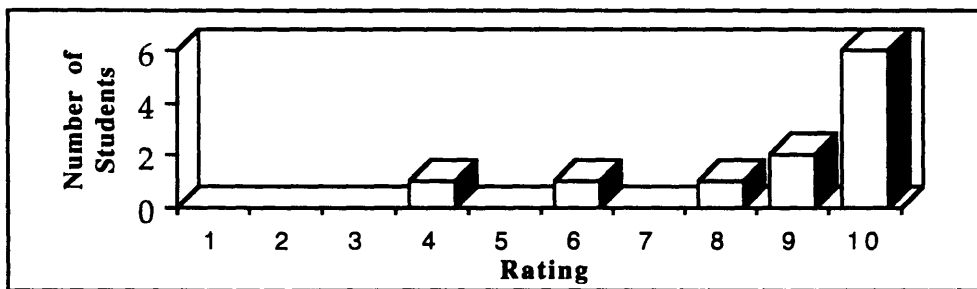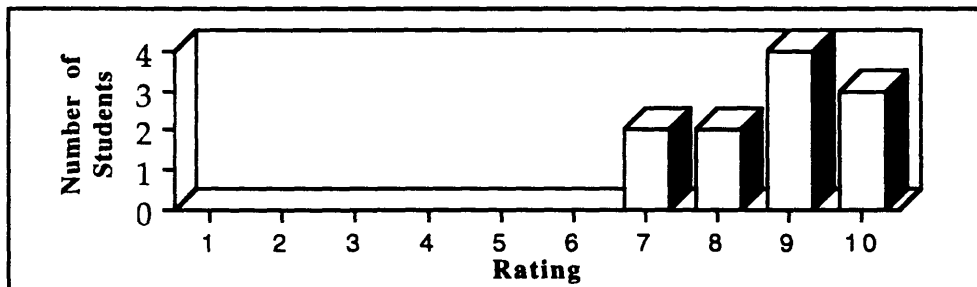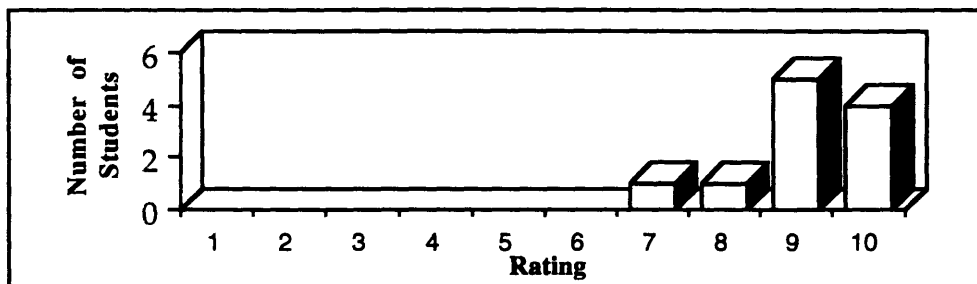
Figure 7.1: Prototype's Ease of Use Compared to the Current Laboratory

7.2: Prototype's Overall Experiment Compared to the Current Laboratory

7.3: Prototype's Educational Value Compared to the Current Laboratory

Having the ability to perform the simulations in the laboratory is a feature very well received by the students. Indeed, they all agreed that it enhanced their understanding of the system by allowing them to vary the plant parameters and controller gains. Moreover, the students appreciated the fact that simulations allowed them to see how the ideal system should act, and to compare those results to the experimental ones. Therefore, it gives a better visual picture of what is being studied. Furthermore, students mentioned that simulations helped them focus on what the watch for during the experiments.

The graphical user interface was deemed key in enhancing the understanding of the laboratory material. Some of the most liked features in the graphical user interface are the clarity of the plots, and the ability to easily change the controller gains and plant parameters. Overall, students judged the graphical user interface easy to use and learn. They estimated the time to become familiar with it at 20 minutes. Taking into consideration that the same structure of the graphical user interface is used for all the laboratory experiments, this time is insignificant when divided over the nine or ten laboratory experiments performed during a semester. Most students, after one or two experiments, felt comfortable enough with the graphical user interface to perform the next experiments with little help and instruction.

Overall, the students considered both the electronics module and the fluids module "comfortable" in terms of their perceived safety and robustness. In particular, the "Emergency Stop" push button was considered a valuable feature. Students appreciated the fact that there is no complicated wiring in the electronics module left for the student to do or see. The electronics module conceals some information not relevant to the experiments and permits students to focus on the control concepts being illustrated. The main attributes of the fluids system, according to the students, are: the possibility of changing the plant parameters by adjusting the resistance values of the needle valves, its compact design, and its visibility. The visibility refers to the ability to observe the water level in the tanks and connecting tubes.

For an evaluation of the electromechanical module, refer to [48].

Suggested Improvements

Though most of the comments from the students were positive, some areas of improvement or design reconsiderations were outlined.

A few students noted that the graphical user interface window and text were too small to be viewed from a distance, and therefore should be enlarged. Moreover, they suggested that the graphical user interface should allow students to graph the simulation

and experimental results on the same plot.

Some, who judged the electronics module as too bulky, suggested relocating it to allow for the computer and the physical modules to be adjacent.

On the fluids module, some students noted that the overflow pipes should be larger, and the number of valves should be increased to make the experiments even more interesting. Also, the amount of splashing should be reduced, and a measuring device along Tank 2 should be added.

<u>Summary</u>

In general, it seems that the students enjoyed performing the experiments on the new apparatus and saw some radical improvements from the current laboratory. They qualified the prototype System Dynamics and Controls Laboratory as easy to use and fun, therefore enhancing the learning ability of the students. Thus, the material was considered more approachable through this set-up. As a result, they were enthusiastic enough about the new laboratory design to recommend it to other students interested in control theory.

CHAPTER 8

CONCLUSION

From the literature reviewed, it seems that a number of schools are trying to renovate or create laboratories to teach students system dynamics and controls. The prototype laboratory described in this thesis not only aims to serve MIT's needs, but also to present a framework which other schools can follow while developing their own System Dynamics and Controls Laboratories.

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Appendix A: Course Descriptions Following MIT Bulletin [29]

Course number/name: **2.02 Introduction to Systems Dynamics**
Prerequisites: 8.01 (Physics I), 18.02 (Calculus)
Level: Undergraduate
Terms offered: Fall, Spring
Units: 4-Lecture units; 0-Lab units; 8-Preparation units
Course type: Required
Course description:

Dynamic modeling by linear and nonlinear lumped multiport elements of physical systems. Unified treatment of active and passive mechanical, fluid, electrical, thermal, and electronic devices and systems. Concept of state and state variables. Formulation and solution of state equations by direct analysis, and by digital computer methods. Dynamic response and stability of linear systems. System functions, pole-zero configurations, and their interpretation. Generalized impedance and source equivalents. Extensive use of engineering examples.

Course number/name: **2.03J Dynamics**
Prerequisites: 2.01 (Mechanics of Solids), 2.02 (Introduction to System Dynamics), 18.03 (Differential Equations) or 13.015 (Mathematical Methods in Ocean Engineering)
Level: Undergraduate
Terms offered: Fall, Spring
Units: 4-Lecture units; 0-Lab units; 8-Preparation units
Course type: Required
Course description:

Dynamics of lumped and continuous models of mechanical, electrical, and electromechanical systems. Kinematics and dynamics of rigid bodies in two- and three-dimensional motions. Formulation of equations of motion by momentum principles and Lagrange's equations. Behavior of linearized models: natural modes and frequency response of lumped systems, wave transmission and reflection in continuous systems.

Course number/name: **2.14 Control System Principles**
Prerequisites: 2.02 Introduction to Systems Dynamics
Level: Undergraduate
Terms offered: Fall, Spring
Units: 3-Lecture units; 2-Lab units; 7-Preparation units
Course type: Restricted Elective
Course description:

Introduction to analysis and synthesis of feedback systems. Functional description of linear and nonlinear systems. Block diagrams and signal flow graphs. State-space representation of dynamical systems. Transient response using convolution integral and computational techniques. Root locus and frequency response methods. Performance indices and error criteria. Controller realization. Examples of pneumatic, hydraulic, electronic, and electromechanical control systems.

Course number/name:	**2.151 Advanced System Dynamics and Control**
Prerequisites:	2.02 (Introduction to System Dynamics), 2.14 (Control System Principles) and 18.06 (Linear Algebra)
Level:	Graduate
Terms offered:	Fall, Spring
Units:	3-Lecture units; 0-Lab units; 9-Preparation units

Course description:

Analytical and graphical descriptions of state-determined dynamic physical systems; time and frequency domain representations; system characteristics - controllability, observability, stability; linear and nonlinear system characteristics using feedback, State observers, Kalman filters. Modeling/performance trade-offs in control system design. Emphasis on application of techniques to physical systems.

Course number/name:	**2.830 Control of Manufacturing Processes**
Prerequisites:	2.14 (Control System Principles) or 15.075 (Applied Statistics)
Level:	Graduate
Terms offered:	Spring
Units:	3-Lecture units; 0-Lab units; 9-Preparation units

Course description:

Process control in manufacturing processes. Discrete system feedback control theory, empirical/adaptive modeling, and basic process physics understanding. A general framework for modeling and control manufacturing processes is developed. Various existing forms of process control are studied, including off-line optimization, statistical process control, and real-time machine and process control. The control approach to process physics is examined in the context of specific manufacturing processes, including metal working, polymer processing, and semiconductor processing.

Appendix B: Class Enrollment Data

Year	Semester	Course # 2.02	Course # 2.03J	Course # 2.14
1994	Fall	118	129	54
	Spring	57	46	64
1993	Fall	119	98	67
	Spring	68	43	62
1992	Fall	162	117	78
	Spring	70	40	71
1991	Fall	141	96	94
	Spring	43	42	109
1990	Fall	142	96	75
	Spring	67	72	110
1989	Fall	141	118	81
	Spring	86	69	103

Table B.1: Class Enrollment Data

Appendix C: Faculty Interaction

Mechanical Engineering Dept. at MIT

NAME	# OF MEETINGS
Prof. A. M. Annaswamy	2
Prof. H. Assada	1
Prof. S. H. Crandall	1
Prof. D. C. Gossard	1
Prof. D. E. Hardt	1
Prof. N. J. Hogan	2
Prof. J. H. Lienhard	1
Prof. B. B. Mikic	1
Prof. I. L. Paul	1
Prof. D. Rowell	1
Prof. W. P. Seering	2
Prof. T. B. Sheridan	1
Prof. A. H. Slocum	1
Prof. J-J. E. Slotine	2
Prof. D. L. Trumper	2
Prof. D. G. Wilson	1
Prof. K. Youcef-Toumi	1

Other Departments at MIT

Prof. C. Chryssostomidis (Ocean Engineering)	1

Outside MIT

Prof. W. Durfee (University of Minnesota)	1 & contact by e-mail
Prof. J. Eaton (Stanford University)	contact by e-mail
Prof. J. Henry (University of Tennessee, Chattanooga)	contact by e-mail
Prof. G. King (Purdue University)	contact by e-mail
Prof. B. Shafai (Northeastern University)	1
Prof. Z. Shiller (University of California, Los Angeles)	1
Prof. J. Vagners (University of Washington)	1 & contact by e-mail
Prof. B. Wilson (Northeastern University)	1

Appendix D: Typical Semester Layout for 2.14

2.14 Lab Schedule

Week # 1		X
Week # 2	Lab #1	Modeling
Week # 3	Lab #2	Modeling
Week # 4	Lab #3	1rst Order System
Week # 5		X
Week # 6	Lab #4	2nd Order / Feedback Control
Week # 7	Lab #5	2nd Order / Feedback Control
Week # 8		X
Week # 9	Lab #6	2nd Order / Stability
Week #10	Lab #7	Root Locus
Week #11		X
Week #12	Lab #8	Frequency Response
Week #13	Lab #9	Design
Week #14		Design

X = No lab this week.

2.14 Student Interaction Between System A and B
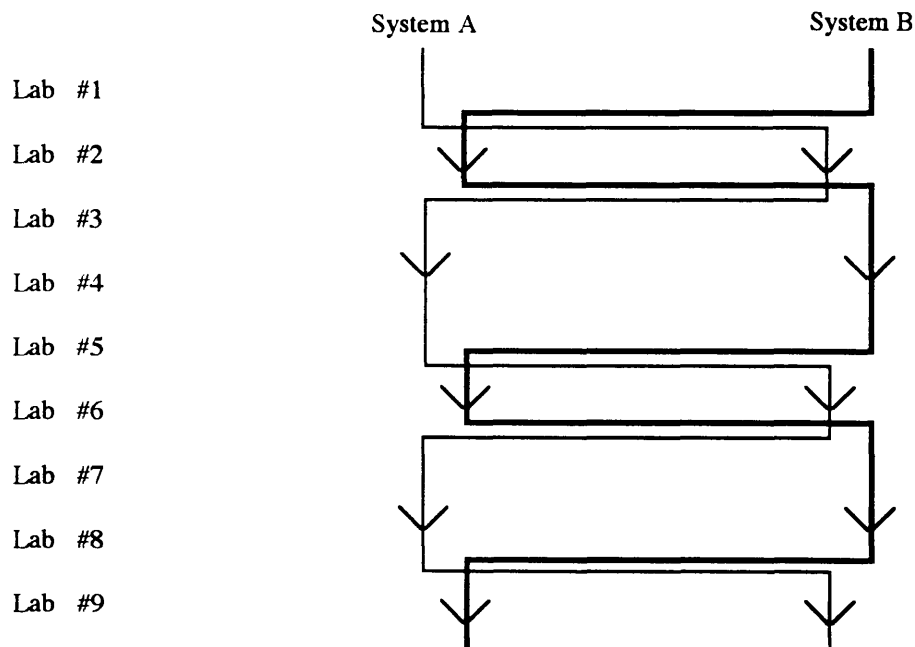
Figure D.1: Proposed Interaction Between Systems A and B

Appendix E: Teacher Assistant Proposed Schedule

Current 2.14 Teacher Assistant Schedule

Total # of hrs. available per term	20hr/wk * 13wks	= 260 hrs

Hrs. spent in lab sessions	9labs * 2.75hr/lab * 6sect.	(148.5 hrs)
Hrs. spent grading	9labs * 5hr/lab	(45 hrs)
Hrs. spent preparing the labs	9labs * 3hr/lab	27 hrs)
Hrs. spent in lectures	3hr/wk * 13wks	(39 hrs)

Total # of hrs. spent per term	(259.5 hrs)

Proposed 2.14 Teacher Assistant Schedule

Total # of hrs. available per term	20hr/wk * 13wks	= 260 hrs

For 2.14

Hrs. spent in lab sessions	9labs * 2.15hr/lab * 6sect.	(121.5 hrs)
Hrs. spent grading	9labs * 4hr/lab	(36 hrs)
Hrs. spent preparing the labs	9labs * 2hr/lab	(18 hrs)
Hrs. spent in lectures	3hr/wk * 13wks	(39 hrs)

Total # of hrs. spent in 2.14 per term	(214.5 hrs)

• The teacher assistant has 260-214.5=45.5 hrs available 2.02, for example.

For 2.02

Hrs. spent in lab sessions	3labs * 2.25hr/lab * 4sect.	(27 hrs)
Hrs. spent grading	3labs * 4hr/lab	(12 hrs)
Hrs. spent preparing the labs	3labs * 2hr/lab	(6 hrs)

Total # of hrs. spent in 2.02 per term	(45 hrs)

Total # of hrs. spent per term	214.5 hrs + 45 hrs = (259.5 hrs)

Appendix F: Proposed Prototype Laboratory Floor Plan
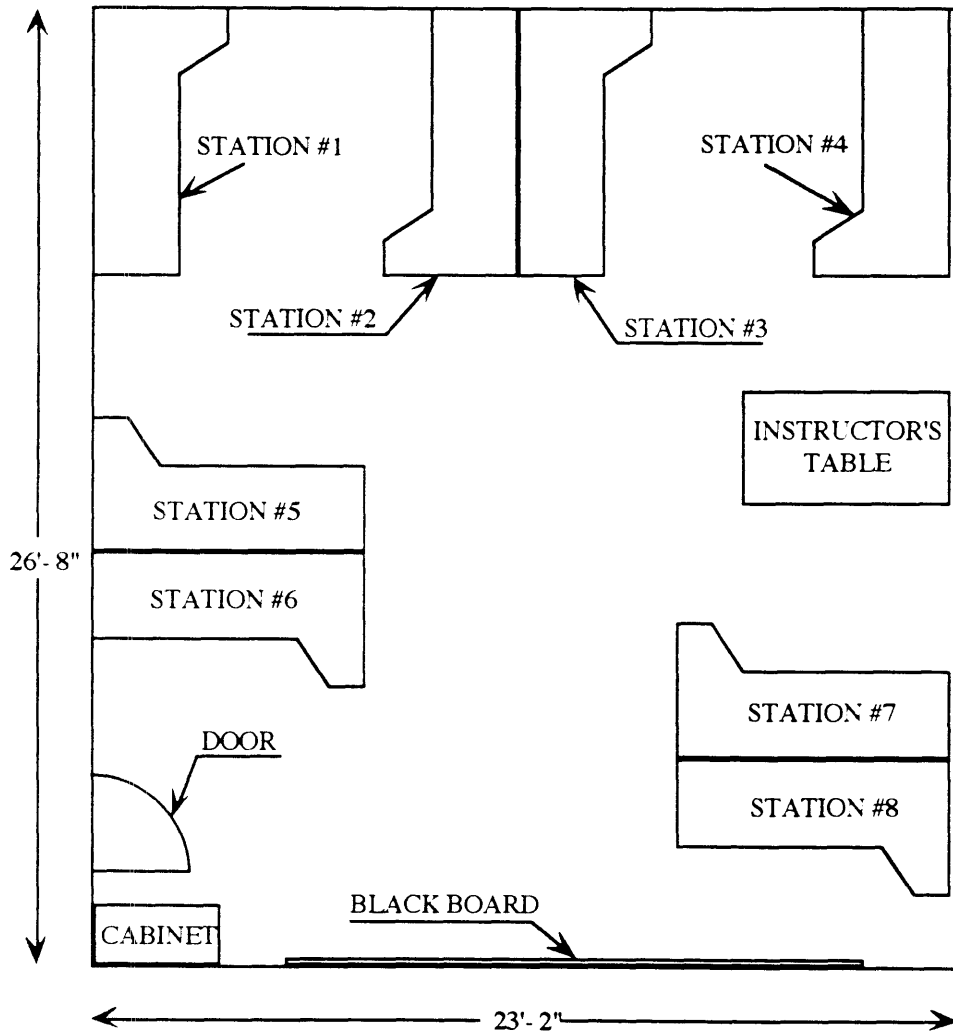
Figure F.1: Proposed Laboratory Floor Plan

Appendix G: Linearized Equations & Transfer Functions of the Water Level Control System

First Order System

Figure G.1: First Order System
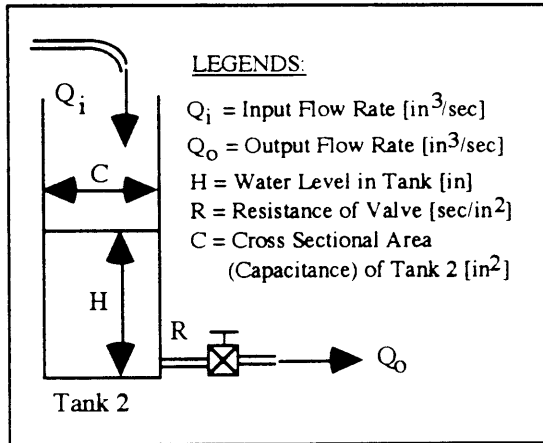
- Linearized Equations:

$$Q_o = \frac{H}{R}$$

$$CdH = (Q_i - Q_o) \, dt$$

- Transfer Function:

$$\frac{H(s)}{Q_i(s)} = \frac{R}{RCs + 1}$$

Coupled Tanks System

Figure G.2: Coupled Tanks System

- Linearized Equations:

$$Q_1 = \frac{H_1 - H_2}{R_1}$$

$$C_1 dH_1 = (Q_i - Q_1) \, dt$$

$$C_2 dH_2 = (Q_1 - Q_o) \, dt$$

$$Q_o = \frac{H_2}{R_2}$$

- Transfer Function

$$\frac{H_2(s)}{Q_i(s)} = \frac{R_2}{C_1 R_1 C_2 R_2 s^2 + (C_1 R_1 + C_1 R_2 + C_2 R_2)s + 1}$$

Decoupled Tanks System
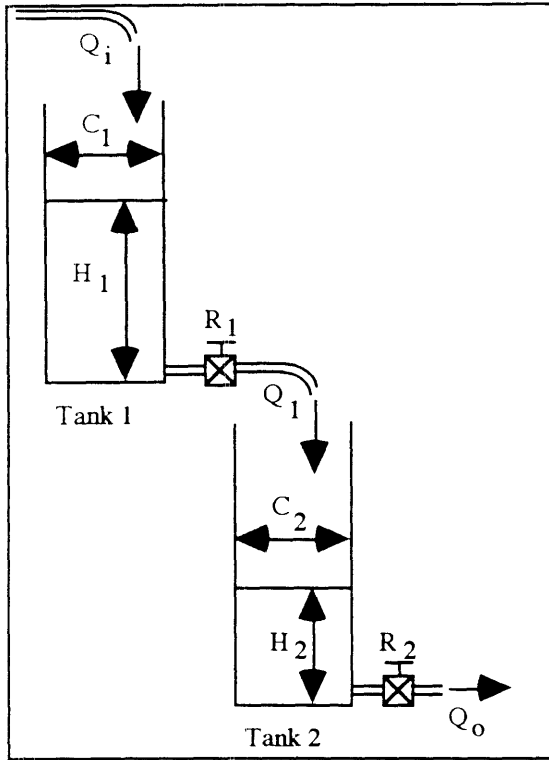
Figure G.3: Decoupled Tanks System

• Linearized Equations:

$$Q_1 = \frac{H_1}{R_1}$$

$$C_1 dH_1 = (Q_i - Q_1)\, dt$$

$$C_2 dH_2 = (Q_1 - Q_o)\, dt$$

$$Q_o = \frac{H_2}{R_2}$$

• Transfer Function

$$\frac{H_2(s)}{Q_i(s)} = \frac{R_2}{C_1 R_1 C_2 R_2 s^2 + (C_1 R_1 + C_2 R_2)s + 1}$$

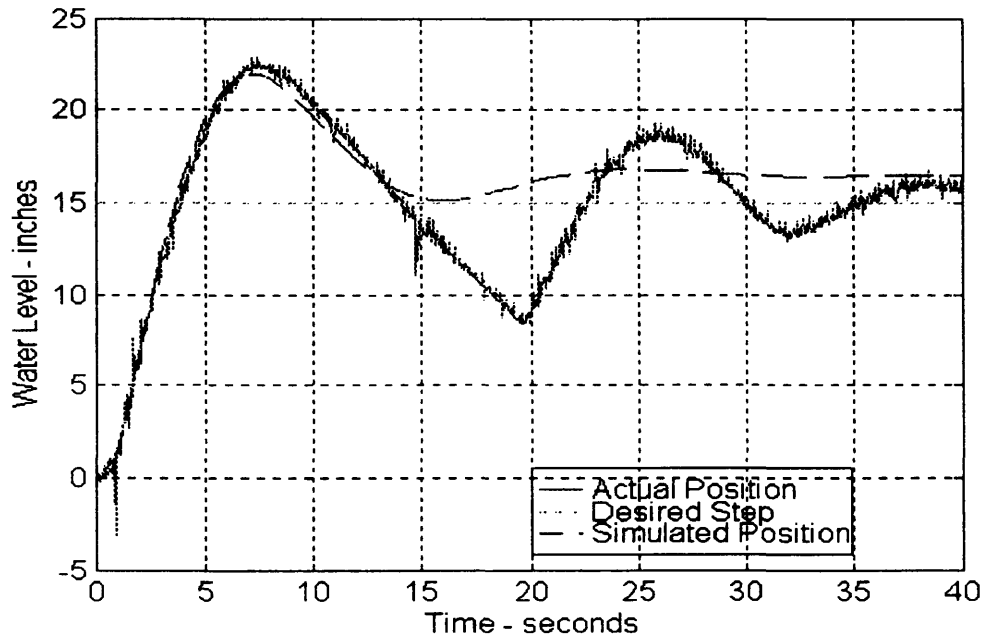## Appendix H: Experimental & Simulation Results for First Order & Second Order Coupled Systems
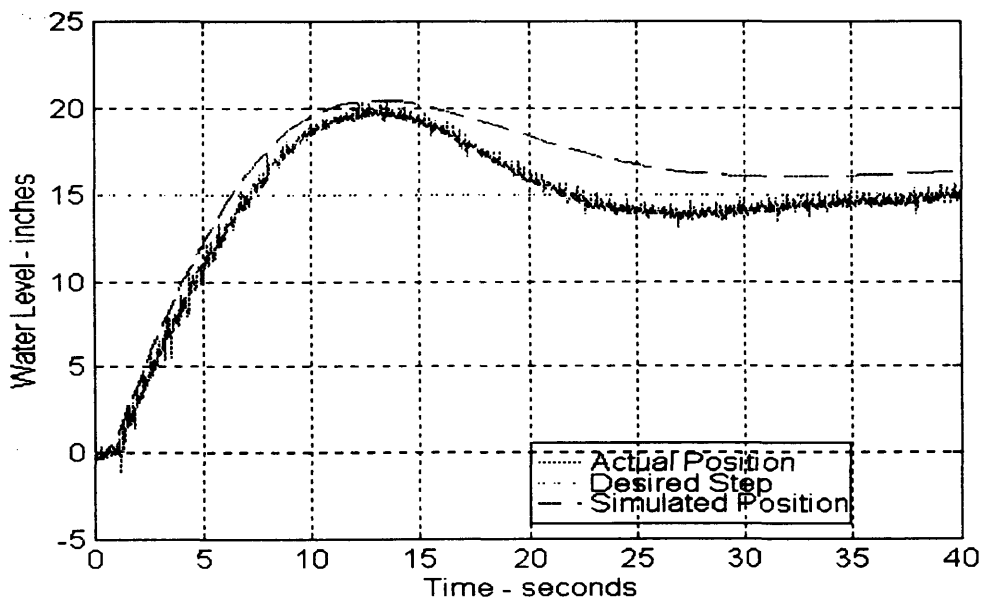

Figure H.1: First Order System Response - Kp=7, Ki=4, Kd=0 - Step = 15

Figure H.2: First Order System Response - Kp=4, Ki=1, Kd=0.05 - Step = 15
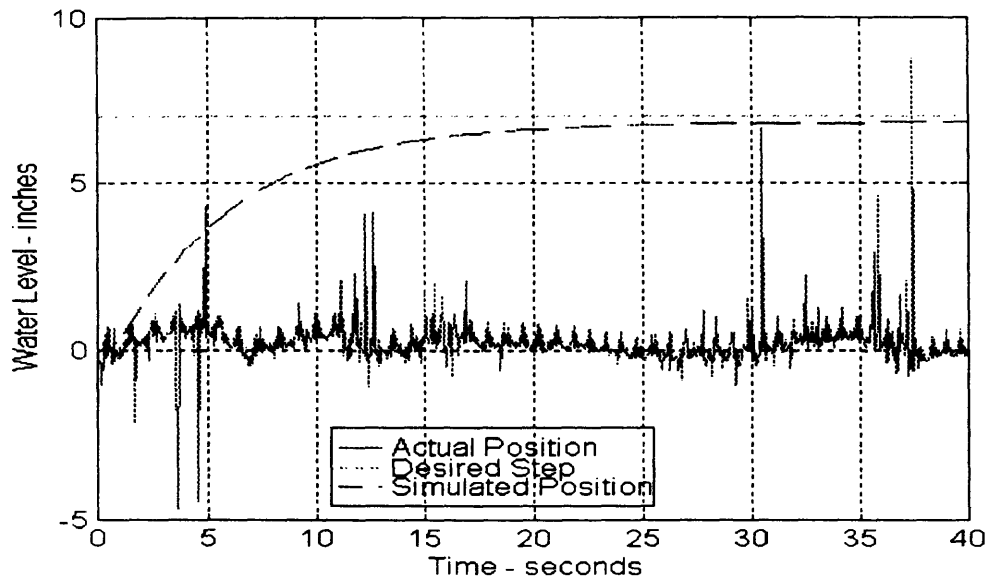
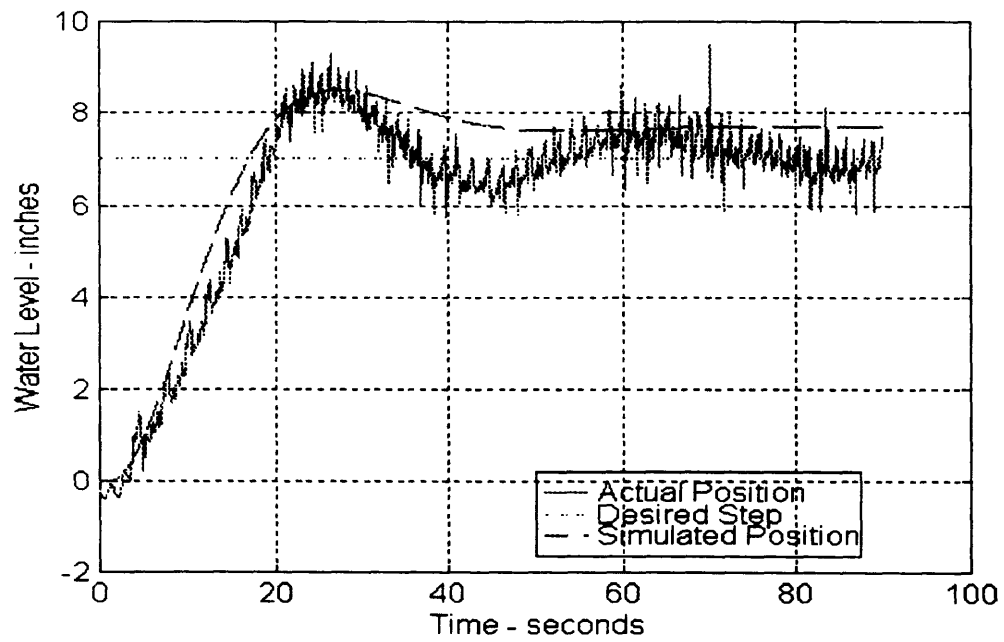Figure H.3: First Order System Response - Kp=3, Ki=0, Kd=0 - Step = 7

Figure H.4: Second Order Coupled Tanks System Response
Kp=12, Ki=0.15, Kd=0 - Step = 7

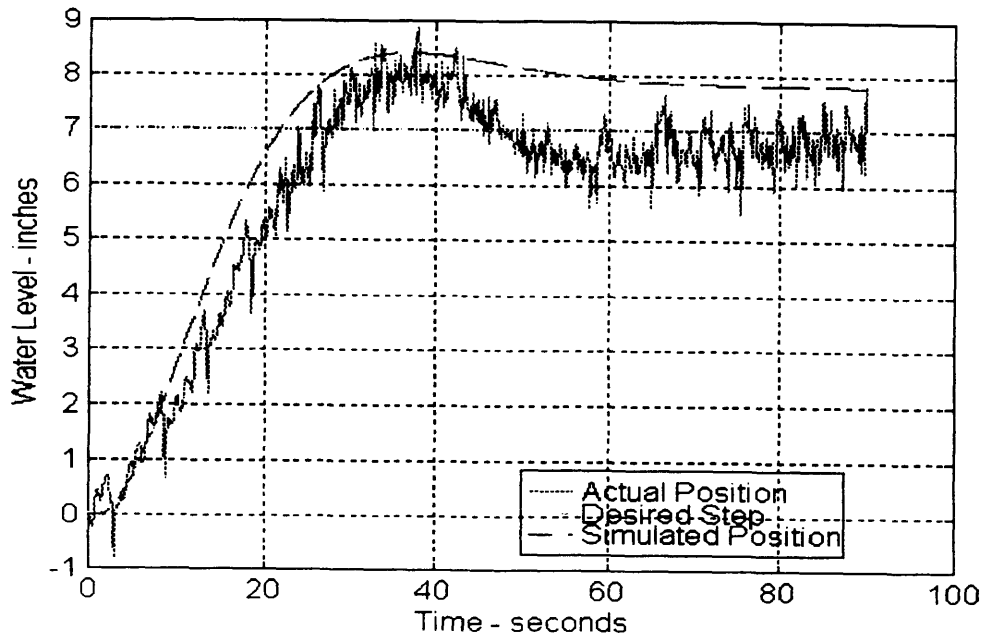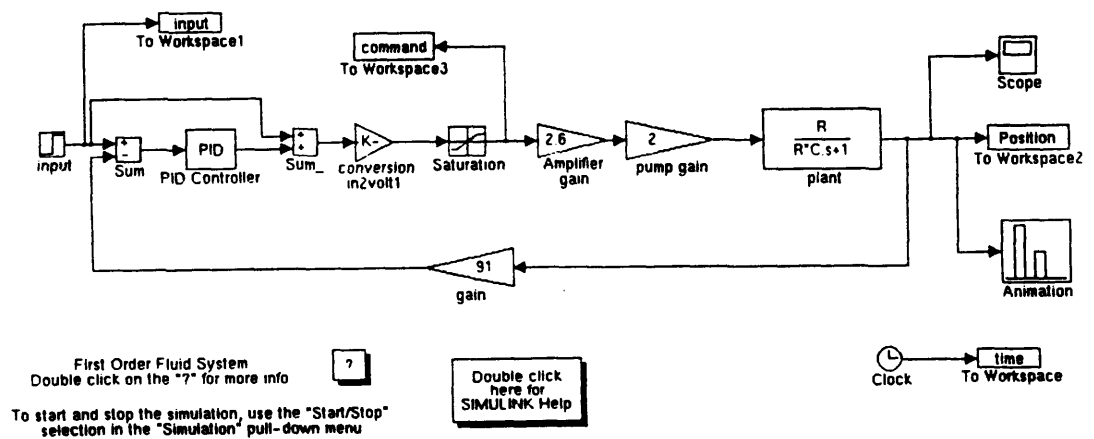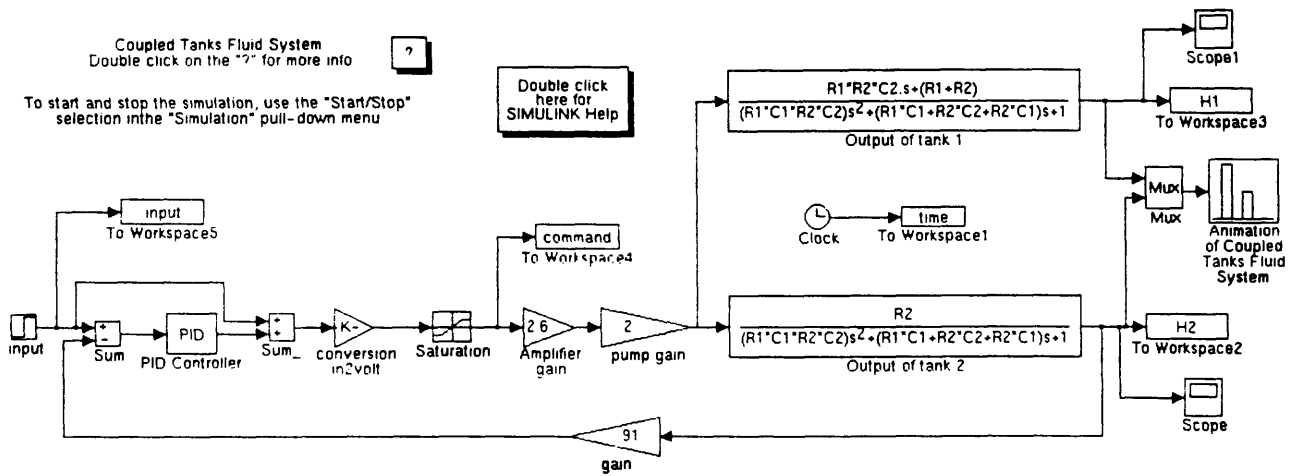Figure H.5: Second Order Coupled Tanks System Response
Kp=8, Ki=0.15, Kd=0.01 - Step = 7

Closed Loop SIMULINK Block Diagram for First Order System

Coupled Tanks Fluid System
Double click on the "?" for more info

To start and stop the simulation, use the "Start/Stop"
selection inthe "Simulation" pull-down menu

?

Double click
here for
SIMULINK Help

$$\frac{R1^*R2^*C2.s+(R1+R2)}{(R1^*C1^*R2^*C2)s^2+(R1^*C1+R2^*C2+R2^*C1)s+1}$$

Output of tank 1

Scope1

H1
To Workspace3

input
To Workspace5

command
To Workspace4

Clock   time
To Workspace1

Mux
Mux

Animation
of Coupled
Tanks Fluid
System

input

Sum   PID   Sum_   K-   Saturation   2 6   2
PID Controller   conversion   Amplifier   pump gain
in2volt   gain

$$\frac{R2}{(R1^*C1^*R2^*C2)s^2+(R1^*C1+R2^*C2+R2^*C1)s+1}$$

Output of tank 2

H2
To Workspace2

Scope

91
gain

Closed Loop SIMULINK Block Diagram for Second Order Coupled Tanks System

Appendix I: Servo-Amplifier Calibration Data

PC Volt *	Actuator Volt **	PC Volt	Actuator Volt
0	0.0267	3	7.845
0.3	0.769	3.25	8.49
0.5	1.302	3.5	9.14
0.8	2.1	3.75	9.78
1	2.62	4	10.43
1.4	3.665	4.25	11.085
1.8	4.71	4.5	11.725
2	5.23	4.75	12.375
2.3	6.01	4.8	12.5
2.6	6.8	4.9	12.755
2.9	7.575	4.99	12.985

Best Fit Curve: $y = 1.9174e\text{-}2 + 2.6023x$
Linearity: $R^2 = 1.000$
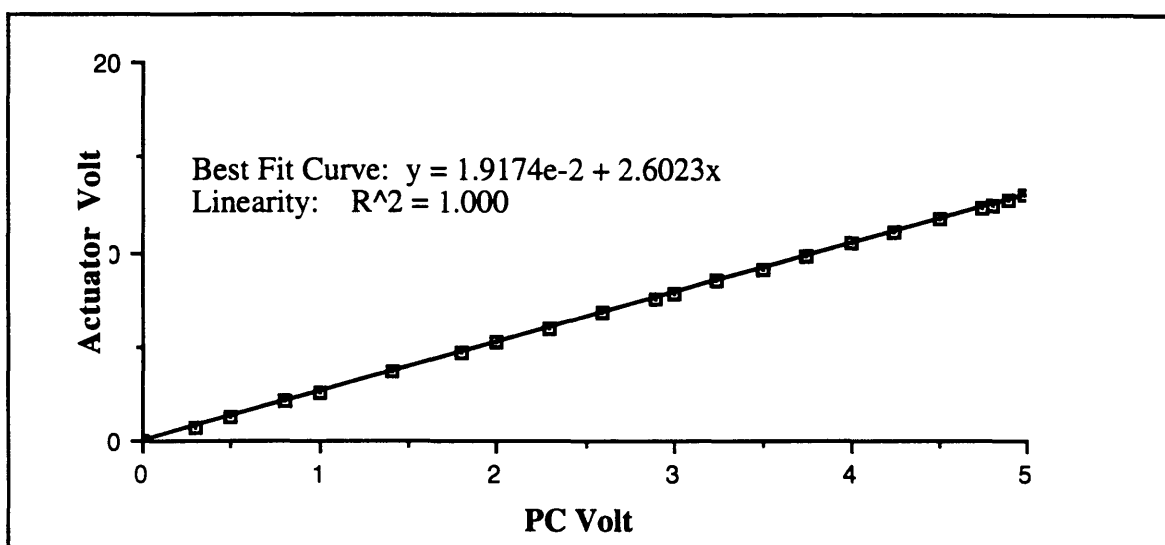
Figure I.1: Voltage-to-Voltage Servo-Amplifier Typical Calibration Curve

* PC Volt represents the output from the multifunction I/O board, corresponding to the servo-amplifier input signal.

** Actuator Volt represents the output of the servo-amplifier, corresponding to the input signal of the actuator (the pump).

Appendix J: Pressure Sensor Calibration Data

Inches*	Voltage **
22	2.955
20	2.755
18	2.56
16	2.35
14	2.15
12	1.949
10	1.747
8	1.54
6	1.337
4	1.128
2	0.918

Best Fit Curve: $y = -7.1091 + 9.8275x$
Linearity: $R^2 = 1.000$
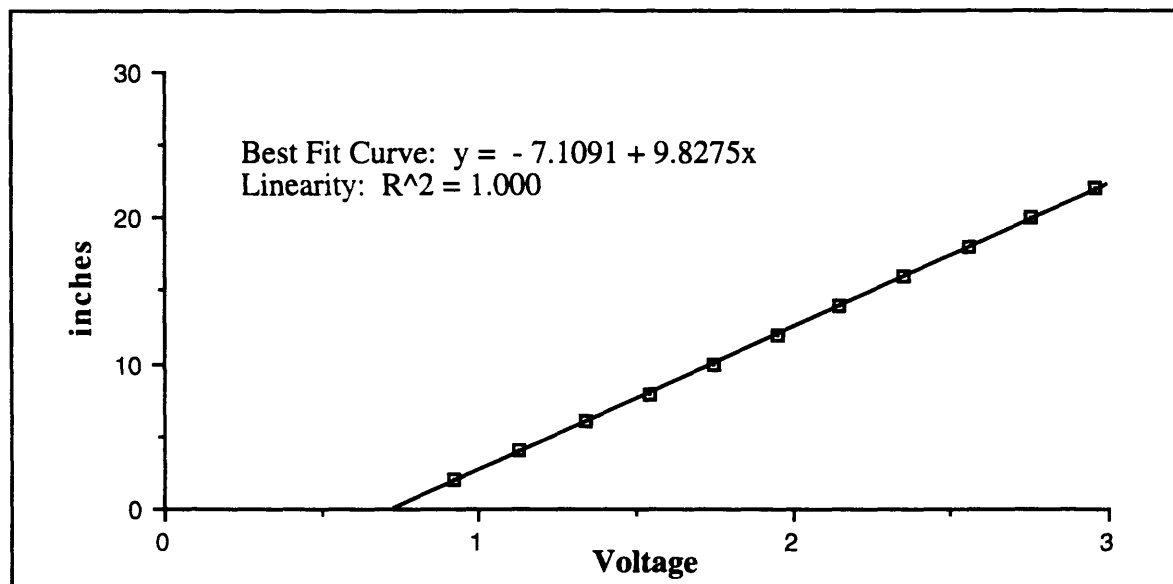
Figure J.1: Typical Pressure Sensor Output Voltage vs. Tank 2 Water Level

* Height of water in Tank 2.

** Voltage output of pressure sensor after gain amplification.

Appendix K: Sample Pre-Laboratory Homework & Laboratory Handout for the Water Level Control System

THIS APPENDIX CONTAINS THE FOLLOWING DOCUMENTS:

- PRE-LAB ASSIGNMENT #3

- SAMPLE HOMEWORK SOLUTION FOR PRE-LAB ASSIGNMENT #3

- LABORATORY HANDOUT #3

- SAMPLE WORKSHEET SOLUTION FOR EXPERIMENT #3

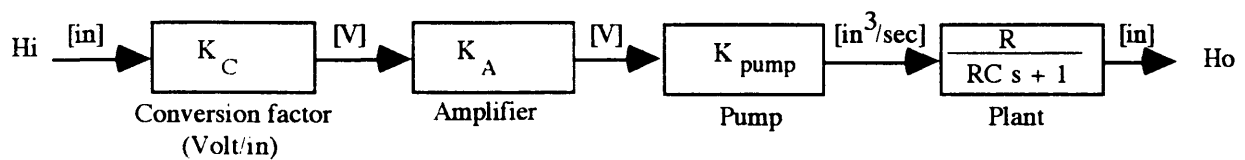THIS DOCUMENTATION REFERS TO FIRST ORDER SYSTEMS (ONE TANK CONFIGURATION).

FLUID SYSTEM

PRE-LAB ASSIGNMENT #3
FIRST ORDER SYSTEM

Question 1:
Given the following Open Loop block diagram (Figure 1):

Hi $\xrightarrow{[in]}$ | K_C | $\xrightarrow{[V]}$ | K_A | $\xrightarrow{[V]}$ | K_{pump} | $\xrightarrow{[in^3/sec]}$ | $\dfrac{R}{RC\,s + 1}$ | $\xrightarrow{[in]}$ Ho

Conversion factor (Volt/in)   Amplifier   Pump   Plant

LEGENDS:

K_C = Conversion Factor from Inches to Volts = 0.0174 V/in

K_A = Amplifier Gain = 2.6 V/V

K_{pump} = Pump Gain (from Voltage to Flow Rate) = 2.4198 in/sec.V

R = Resistance

C = Cross Sectional Area (Capacitance) = 0.785 in

Hi = Reference Input Position [in]

Ho = Output Position [in]

Figure 1: Open Loop Block Diagram

a) Derive the transfer function relating the reference input position (Hi) to the output position (Ho)

b) Derive an expression for the open loop time constant (τ_{ol}).

c) Conclude on the dependence of the open loop time constant (τ_{ol}) on other parameters (step size and resistance R).

Question 2:

Given the following Closed Loop block diagram with a Proportional controller (Figure 2):
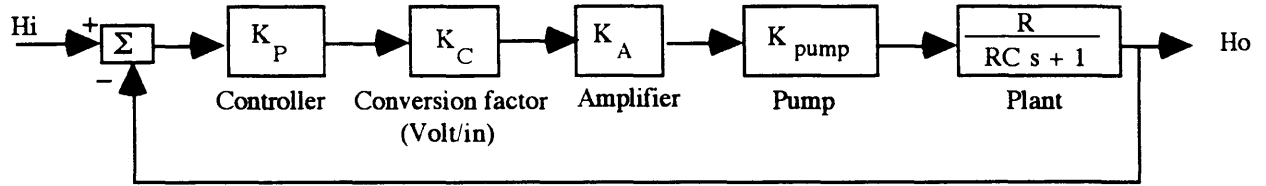
LEGENDS:

K_p = Proportional Controller

Figure 2: Closed Loop Block Diagram

a) Derive the transfer function relating the reference input position (Hi) to the output position (Ho)

b) Derive an expression of the closed loop time constant (τ_{cl}).

c) Conclude on the dependence of the closed loop time constant (τ_{cl}) on other parameters (step size and resistance R).

d) Compare open loop and closed loop time constant.

Question 3:

For the closed loop system with P-control, find an expression for the error using the final value theorem. The error is the difference between the reference input position and the output position.

PRE-LAB ASSIGNMENT #3
FIRST ORDER SYSTEM
ANSWER KEY

Question 1:

a) $\quad TF = \dfrac{H_o}{H_i} = (K_c K_a K_{pump}) \dfrac{R}{RC\,s + 1}$

b) $\quad \tau_{ol} = RC$

c)

τ_{ol} depends only on physical parameters, namely R and C. So, step size should not affect time constant if R and C are not changed.

Note: C cannot be changed since it is the cross-sectional area of the tank. BUT

R is variable   --> as R increases, τ_{ol} increases (slower system)

--> as R decreases, τ_{ol} decrease (faster system)

Question 2:

a) $\quad TF = \dfrac{H_o}{H_i} = \dfrac{K}{RC\,S + 1 + K}$

where $\quad K = K_p K_c K_a K_{pump} R$

b) $\quad \tau_{cl} = \dfrac{RC}{1 + K_p K_c K_a K_{pump} R}$

c)

R is variable & will affect the τ_{cl} if it is changed.

K_c, K_a, & K_{pump} are considered constant throughout the experiments

--> For a closed loop system K_p comes into play for the τ_{cl} & it is variable

as K_p increases, τ_{cl} decreases (faster system)

as K_p decreases, τ_{cl} increases (slower system)

d)
Assuming R & C are not changed.
With open loop control, the time constant is fixed.
With closed loop control, the time constant can be adjusted by varying K_p.

Question 3:

$e_{ss} = \dfrac{1}{1 + K_p K_c K_a K_{pump} R}$

Since everything is constant except K_p, e_{ss} --> 0 as K_p --> 0

FLUID SYSTEM

EXPERIMENT #3
FIRST ORDER SYSTEM

INTRODUCTION

In the previous lab, you were asked to derive three transfer functions on the fluid module either with one tank, or two tanks coupled or uncoupled. A first order system is obtained only when one tank is taken into consideration. Therefore, today's lab will use only one tank.

This laboratory, has 3 main goals.
- We will study the open loop versus closed loop system. This will allow us to illustrate some of the control concepts; mainly, feedback.
- The block diagram that is used to run simulations represents a simplified version of the real system. Therefore, it is important to realize that the simulation results are only as accurate as the model used to represent the real system.
- Finally, we will study the dynamic behaviors of the system by changing the parameters.

Since this is the first lab where you will heavily use Matlab's Graphical User Interface, all the procedures are outlined in great detailed.

OPEN LOOP SYSTEM

In the following two questions, we will try to verify, via simulations and experiments, the conclusions made in the pre-lab exercise on the dependence of the open loop time constant (τ_{ol}) on various parameters.

Question 1:
a) On the open loop system, using Matlab/Simulink, perform three simulations with a reference input step size of 5, 7 and 10 inches respectively. Submit the plots of the height versus time. Is the time constant of the system affected by the changes in step size?

b) For each step size mentioned above, perform two simulations: One where the value of R is 21, and the other with a value of R of 35. Determine what is the effect of changing R on the open loop performance.

Question 2:
a) Using the Real Time Control option on the Graphical User Interface in Matlab's Lab #3 Main Menu, perform experiments on the open loop system for a Reference Step Input Position of 5 and 7 inches.

b) For both plots, derive the system time constant from the settling time (found from the above plots). How does it compare to what you expected from the pre-lab homework.

c) Close the needle valve by approximately turning the handle one turn to increase the value of R. For each one of the step inputs mentioned above, perform the same experiment as in question 2a.

d) How do the experimental results compare to what you expected from theory (refer to questions in the pre-lab homework)?

CLOSED LOOP SYSTEM

In the following three questions, we will try to verify, via simulations and experiments, the conclusions made in the pre-lab exercise on the dependence of the closed loop time constant (τ_{cl}) on various parameters.

Question 3:
On the closed loop system with P-control, using Matlab/Simulink, perform three simulations with Kp set at 2, 5 and 7 respectively for a step size of 10 inches. Submit the plots of the height versus time. Is the closed loop time constant affected by the changes in the value of Kp?

Question 4:
a) For each value of Kp mentioned in Question 3) and a step size of 10 inches, perform two simulations on the closed loop system with P-control: One where the value of R is 21, and the other with a value of R of 35. Determine what is the effect of changing R on the closed loop performance as the value of Kp increases.

b) Observe physically (by running the Real Time Control experiment) how changes in parameters affect the performance of the closed loop system with a P-controller. Run experiments with Kp set at 5 with the valve fully open and partially closed. Repeat the same experiments with Kp set at 7. Relate to what you expected from simulations (refer to trends only).

Using your newly acquired familiarity of the Matlab Graphical User Interface, and knowledge of closed loop feedback concepts you are ready to perform a more interesting set of experiments.

Question 5:

Your objective is to find the appropriate value for Kp to meet the following specifications on the closed loop transient response.
        Reference Step Input Position = 15 in
        2% Settling Time < 10 sec
        Steady State Error < 0.5 in

For this question, the needle valve is fully open.

a) Find the value of Kp using the simulation option on the GUI to meet the above specifications. The resistance R should be set back to 21 for this question. Also, in your Simulink block diagram, don't forget to set the step size to 15.

b) Using the value of Kp you found in Question 5 a), run the Real Time Control option on the graphical user interface in Matlab, and print out the plot of Position versus

Time. (Don't forget to fully open the needle valve!)

c) Compare the experimental plot to the one obtained through simulations. How do the values of the settling time and steady state error compare?

COMMENTS / OBSERVATIONS

Question 6:
Explain in your own words what you think are the advantages and/or disadvantages of using a closed loop system over an open loop one from what you have learned in this lab.

Hint on some questions you might want to answer:
a) Compare the simulation response of feedback control over open loop control in terms of accuracy, sensitivity, transient response, and stability.

b) What is the effect of changing physical parameters on closed loop performance compared to open loop performance.

FLUID SYSTEM

ASSIGNMENT #3 ANSWER SHEET
FIRST ORDER SYSTEM

OPEN LOOP SYSTEM

Question #1:

a)
The following plot represents the Simulated Water Level
Displacement vs. Time for three different input steps: 5, 7
and 10 inches.

After each simulation you should evaluate one of the following commands depending on the step size.
o_step5
o_step7
o_step10
Finally when you are satisfied with the data that you obtained, evaluate the next command to plot all 3 curves on the same graph
o_plt

Simulated Open Loop Step Response

b)
* Given a step size of 5 inches, the following plot
  represents the Simulated Water Level Displacement vs.
 Time for two different resistance values: 21 and 35.

First evaluate one of the following commands after each simulation to save the data.
o_r7
o_r15
Finally evaluate the following command to plot both curves with different resistance for a given step.
o_rplt

Simulated Open Loop Step Response

*   Given a step size of 7 inches, the following plot
    represents the Simulated Water Level Displacement vs.
    Time for two different resistance values: 21 and 35.

First evaluate one of the following commands after each simulation to save the data.
o_r7
o_r15
Finally evaluate the following command to plot both curves with different resistance for a given step.
o_rplt

Simulated Open Loop Step Response
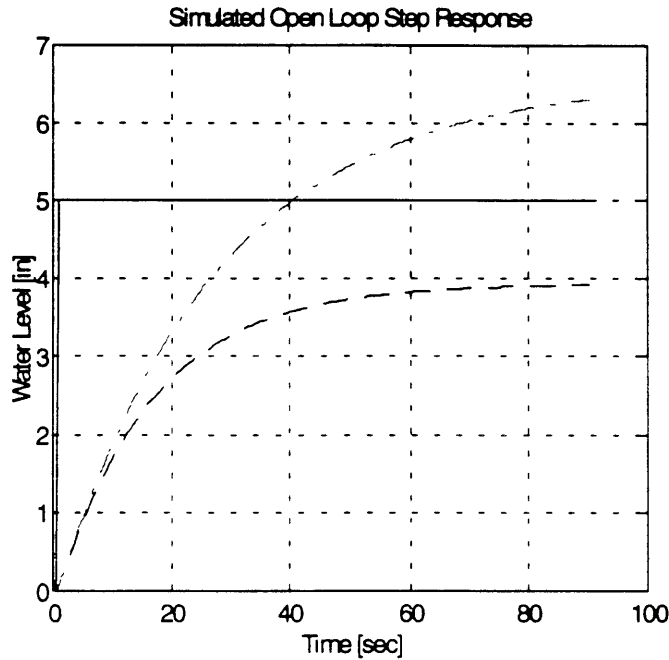
* Given a step size of 10 inches, the following plot
  represents the Simulated Water Level Displacement vs.
  Time for two different resistance values: 21 and 35.

First evaluate one of the following commands after each simulation to save the data.
o_r7
o_r15
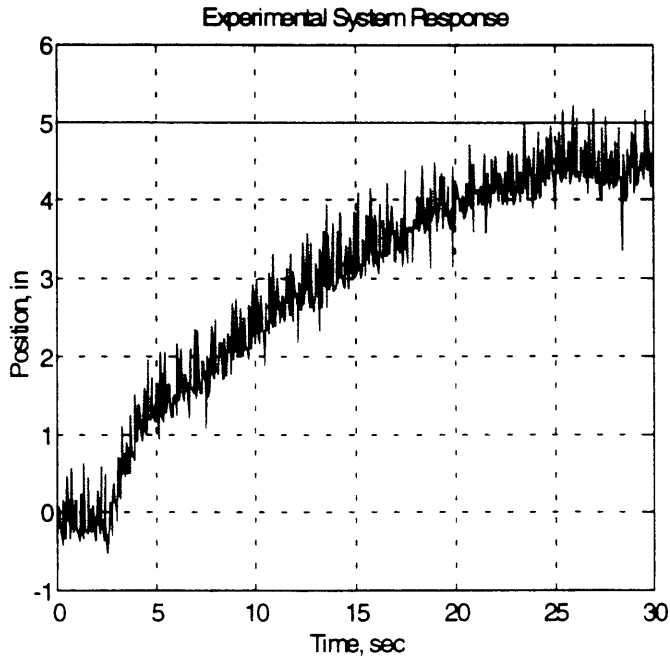*Finally evaluate the following command to plot both curves with different resistance for a given step.*
o_rplt

Simulated Open Loop Step Response
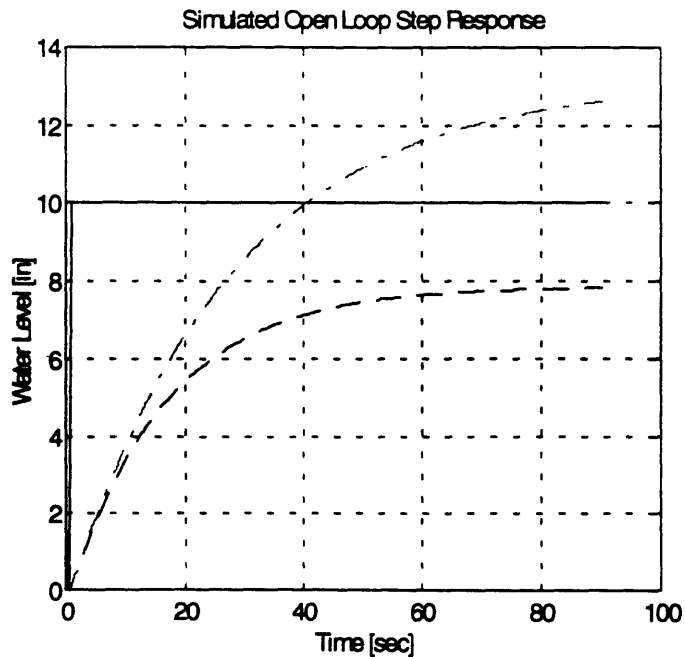
Question #2:

a) & b)

* Given a step size of 5 inches, the following plot
  represents the Actual Water Level Displacement vs. Time
  when the valve is fully open.

o_act

Experimental System Response

* Given a step size of 7 inches, the following plot
  represents the Actual Water Level Displacement vs. Time
 when the valve is fully open.

o_act

Experimental System Response

c)
* Given a step size of 5 inches, the following plot
  represents the Actual Water Level Displacement vs. Time
  when the valve is closed one turn.

o_act

Experimental System Response

* Given a step size of 7 inches, the following plot
  represents the Actual Water Level Displacement vs. Time
  when the valve is closed one turn.

o_act

Experimental System Response
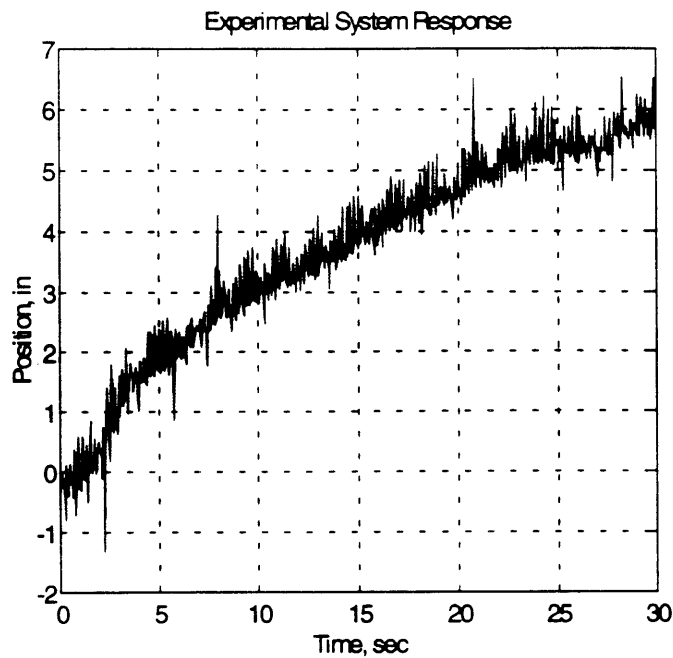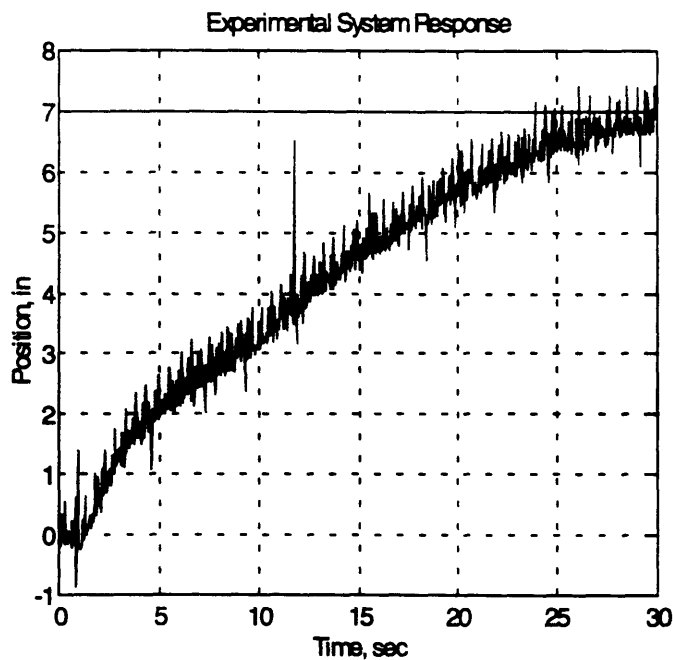
d)
There are discrepancies between theoretical and experimental values probably due to the following reasons:
- Theoretical resistance values of 21 and 35 are not good approximations of the actual values corresponding to fully open and closed one turn, respectively.
- Some non ideal parts of the plants dynamics have not been taken into consideration in our simulations.

CLOSED LOOP SYSTEM

Question #3:

Given a step of 10 inches, the following plot represents the simulated response of the closed loop first order system for three different values of Kp: 2, 5, and 7.

After each simulation you should evaluate one of the following commands depending on the value of Kp.
c_kp5
c_kp1
c_kp2
Finally when you are satisfied with the data that you obtained, evaluate the next command to plot all 3 curves on the same graph
c_plt

Simulated Closed Loop Step Response
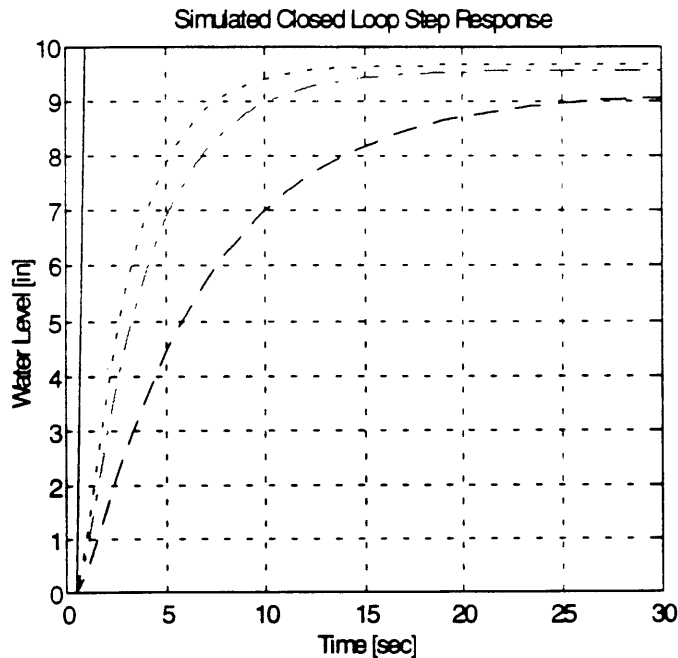
Question #4:
a)
* Given a step of 10 inches and Kp = 2, the following plot represents the simulated response of the closed loop first order system for two different resistance values: 21 and 35.
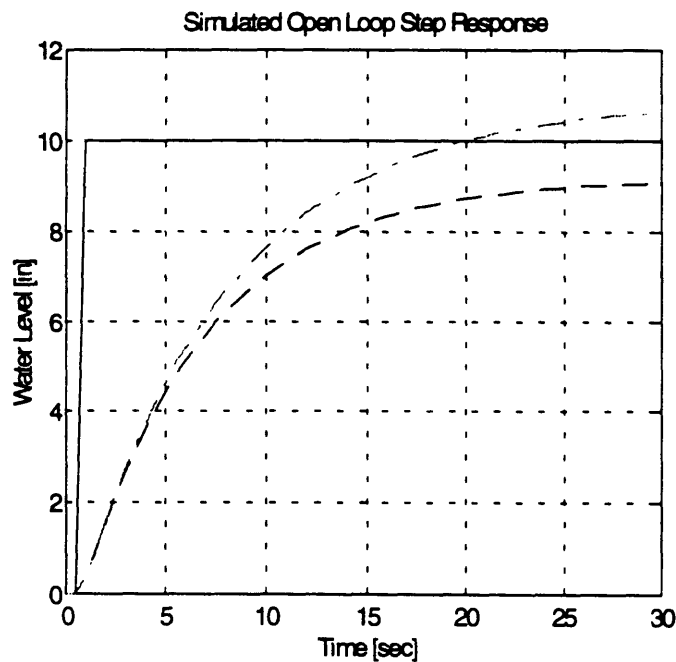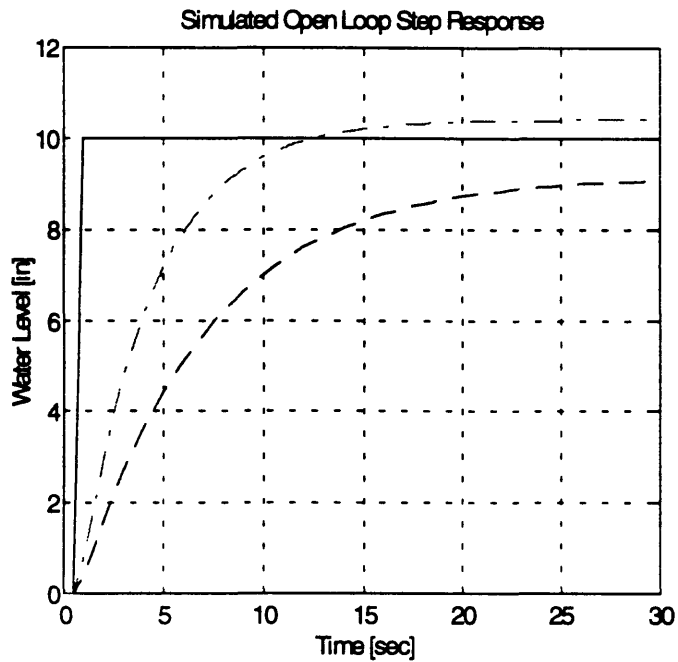
First evaluate one of the following commands after each simulation to save the data.
c_r7
c_r15
Finally evaluate the following command to plot both curves with different resistance for a given step.
c_rplt

Simulated Open Loop Step Response

* Given a step of 10 inches and Kp = 5, the following plot represents the simulated response of the closed loop first order system for two different resistance values: 21 and 35.

First evaluate one of the following commands after each simulation to save the data.
c_r7
c_r15
Finally evaluate the following command to plot both curves with different resistance for a given step.
c_rplt

Simulated Open Loop Step Response

*   Given a step of 10 inches and Kp = 7, the following plot
    represents the simulated response of the closed loop
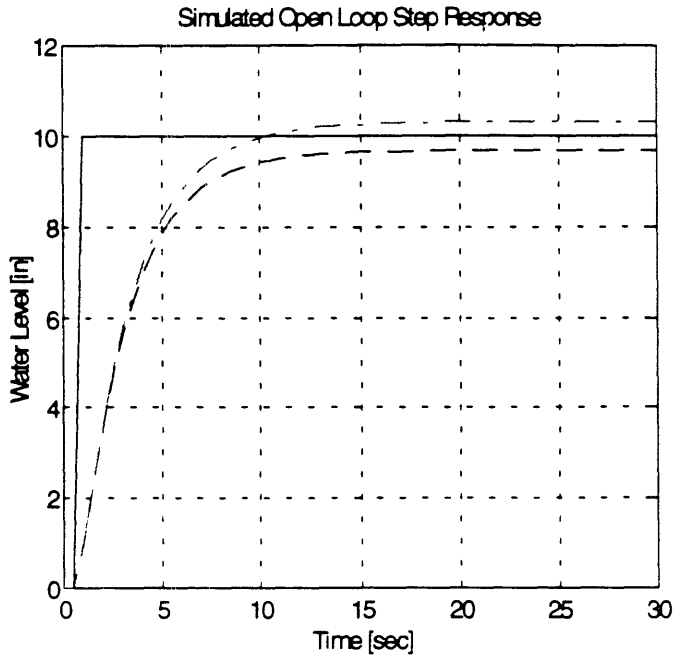   first order system for two different resistance values:
    21 and 35.

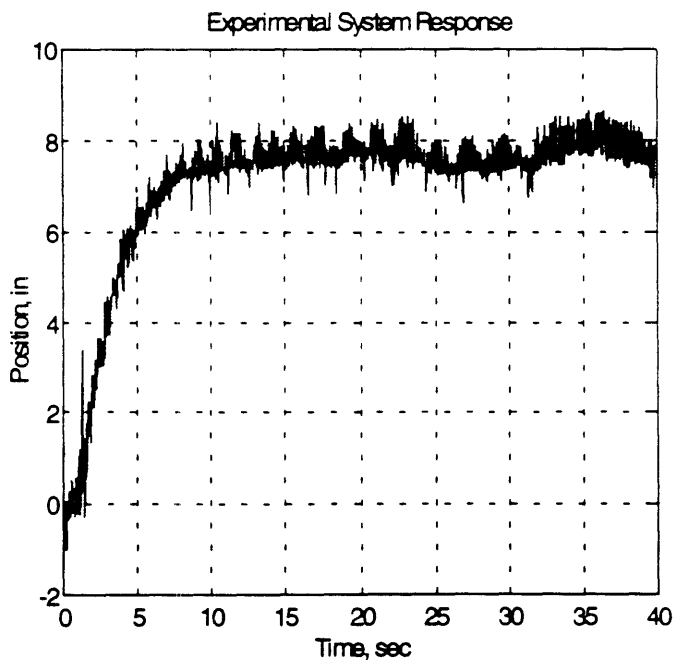*First evaluate one of the following commands after each simulation to save the data.*
`c_r7`
`c_r15`
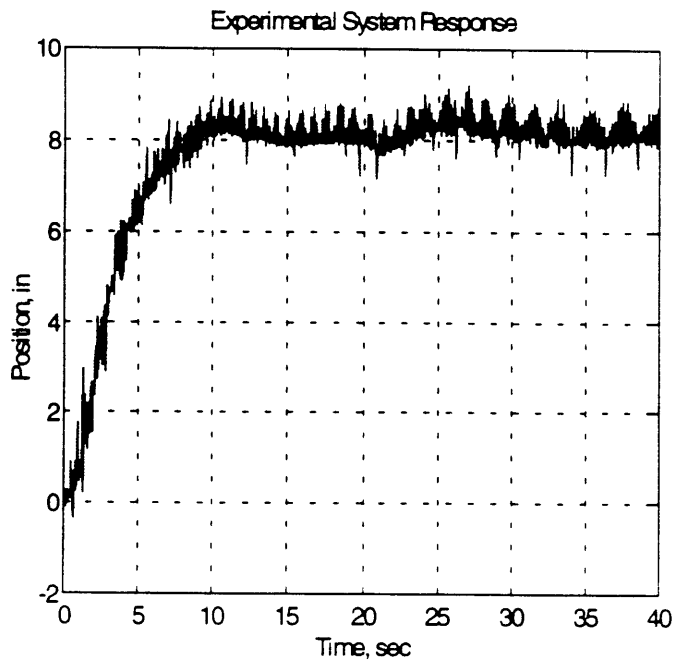*Finally evaluate the following command to plot both curves with different resistance for a given step.*
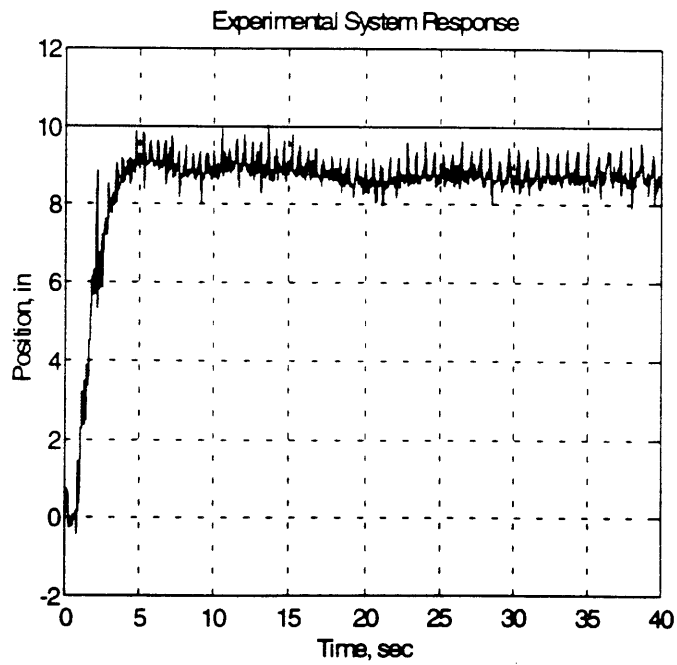`c_rplt`

Simulated Open Loop Step Response

b)
Kp = 5 without resistance (fully open valve)
c_act

Experimental System Response

Kp = 5 with resistance (valve turned 2 turns)
c_act

Experimental System Response

Kp = 15 without resistance (fully open valve)
c_act

Experimental System Response

Kp = 15 with resistance (valve turned 2 turns)
c_act

Experimental System Response
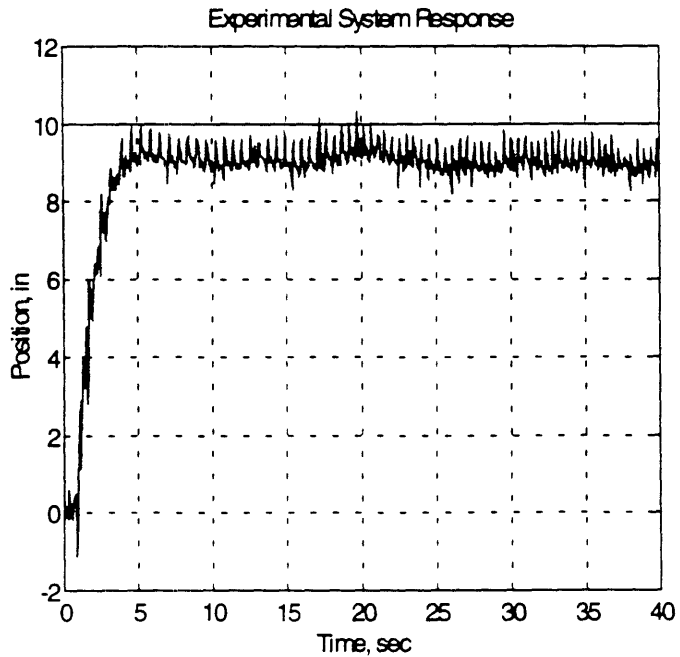
Observations from experimental data:
-   The closed loop control performs much better than the
    open loop control at achieving the desired step input.
-   It is much less sensistive than the open loop control
    to the changes in resistance values.
-   The higher the value of the controller gain (Kp) the
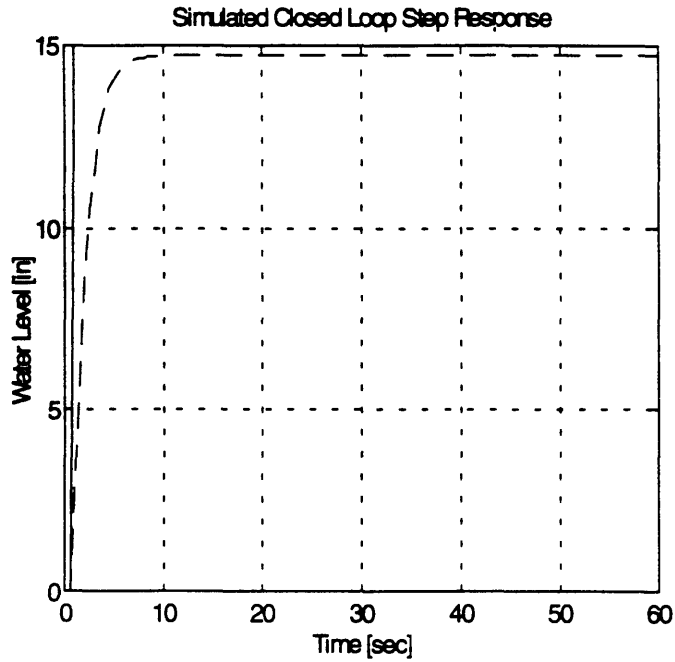   smaller the steady state error.

Question #5:
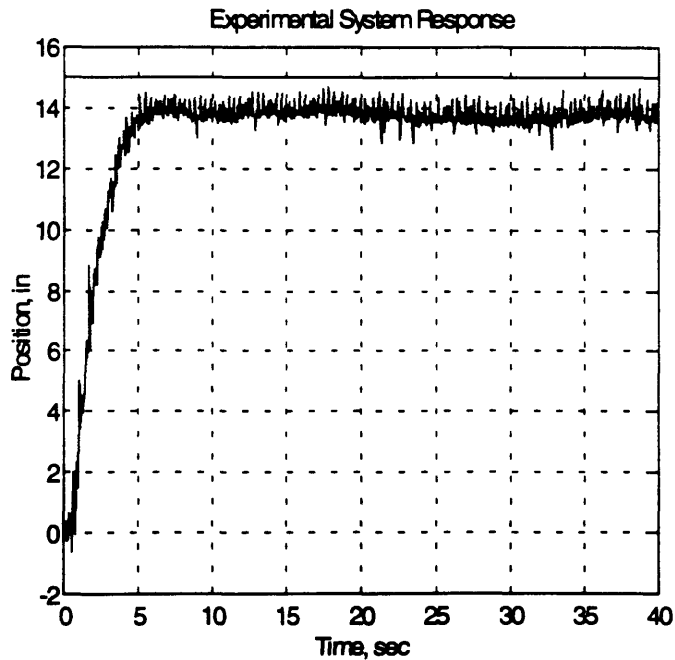
a)

Kp

Kp =
     14

c_kp

Simulated Closed Loop Step Response

b)

c_act

Experimental System Response

c)
Comparison:
The experimental and theoretical curves are very simular:
- In both case the 100% rise time is about 5 sec.
- The experimental steady state error is slightly larger than the simulated one. The former is one inch whereas the latter is approximately 0.3 inches.

Question #6:

Closed loop control allows for better control of the system compared to open loop control.

It is also better at rejecting external disturbances since it is less affected by variations in the plant parameters (resistance)

Appendix L: System Dynamics and Controls Laboratory Survey

In this survey we are mainly seeking to have a better understanding of **how students respond to the overall structure** of the prototype system dynamics and control lab.

Student Profile: **Year:**   _____

                         Major: _____

                         When did you take 2.14?   _____

Which module did you work on?   Electromechanical / Fluid

Please reply to the following question by comparing the prototype lab to the old lab on a scale from 1 to 10 where 1 is "worse than the old lab" and 10 is "better than the old lab."

What was your impression of the prototype lab in terms of the following issues compared to the old lab:

- ease of use

Worse   *Better*
  1   2   3   4   5   6   7   8   9   10

- overall experiment

  1   2   3   4   5   6   7   8   9   10

- Educational value (clarity of concepts illustrated)

  1   2   3   4   5   6   7   8   9   10

1) Were the control concepts covered in the prototype lab well illustrated? How might they be improved?

2) How much does performing simulations and physical experiments in the same lab add to your understanding of the control concepts?

3) Did using the MATLAB GUI enhance your understanding of the lab material?

4) How long did it take you to learn how to use the GUI, and feel comfortable with it? Did this time seem excessive?

5) Did you find the hardware "comfortable" in terms of safety and robustness?
   Electrical Module:

   Fluid Module / Electromechanical Module:

6) What did you like best about:
   the Electrical Module?:

   the Fluid Module / Electromechanical Module?:

7) What needs to be improved in the prototype?
   on the Electrical Module?:

   on the Fluid Module / Electromechanical Module?:

8) Would you recommend this new system dynamics and control laboratory to your best friend? Why?

Any additional comments, thoughts or recommendations are welcome ...

Thanks for your input!