LABORATORY FOR A FIRST COURSE IN MODELING AND AUTOMATIC CONTROL

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ABSTRACT

This paper describes laboratory experiments to support mechanical engineering courses in modeling and automatic control theory. The paper begines with discussions of the goals for the experiments and the constraints under which the experiments must be designed. The course objectives which are supported by the laboratory are teaching of modeling, parameter identification, classical control methods, and digital implementation of control strategies. In addition, the laboratory demonstrates to mechanical engineering students how they can use micro processors in design. The main constraints which influenced the design of experiments to meet these objectives are cost, the large number of students who will use the lab, and the need to vary the experiments regularly. The decision on whether to purchase "canned" experiments or to design and construct personalized systems is considered based on these objectives and constraints. The experiments used at Texas A&M are reviewed and relative success with each is discussed. The experiments include:

1. A compound pendulum which is used to introduce the students to digital data acquisition and parameter identification.
2. A motor driven rotary table which is used for experiments on parameter identification, simulation, and both analog and digital control.
3. A coupled tanks system which is used for experiments on parameter identification and simulation. and a control project.
4. A motorized cart which is very versatile and is used for a variety of modeling, parameter identification, and control experiments on projects.

INTRODUCTION

Many of the students taking a first course in system modeling or control theory find it difficult to relate the theory to the physical world. A laboratory experience where the students can analyze a physical system and compare the results of this theoretical analysis to the actual response of the system can be extremely beneficial in helping the students understand the modelling, analysis and design procedures and retain this knowledge. This paper describes the experiments in a required modeling and controls course taught to sixth semester mechanical engineering students at Texas A&M University. The following sections describe the specific goals of the laboratory material, the constraints on such a laboratory, and the various experiments.

GOALS OF THE LABORATORY

The primary goal for the laboratory is to reinforce the material presented in the classroom. A secondary goal is to introduce mechanical engineering students to analog-to-digital converters, digital-to-analog converters and real time programming to prepare them to use microcomputers in mechanical design. These topics are not covered in lecture or in any other required course in the mechanical engineering curiculum. The experiments involve analog systems, digital systems, and various transducers and actuators. The analog systems include operational amplifiers, motors, gears, pumps, liquid level systems, amplifiers and various mechanical systems modeled using Newton's laws. The experience with digital systems includes real-time programming of a personal computer to perform data acquisition and control tasks with analog-to-digital and digital-to-analog hardware. Transducers such as potentiometers, encoders, tachometers, strain gages, and pressure transducers are also included. Each experiment combines these components to form a dynamic system that exhibits either first or second order linear or nonlinear response and reinforces concepts presented in lecture.

CONSTRAINTS ON LABORATORY DEVELOPMENT

There are a number of practical constraints on developing a laboratory experience for large numbers of students. The first and primary constraint is cost. To achieve the goals of the lab each student must have hands-on experience with a number of devices and adequate instrumentation. Thus, the number of students dictates the number of laboratory stations required. The cost of each lab station can be minimized by taking advantage of the versatility of the personal computer (PC). By providing appropriate software the PC can replace several single purpose instruments; e.g., a digital voltmeter, a strip chart recorder, and an X-Y plotter. At

Texas A&M each lab station is built around a Texas Instruments Professonal Computer (TIPC) equipped with an analog input/output board which contains an analog-to-digital converter (ADC), a digital-to-analog converter (DAC), and a real time clock (RTC). This system is used for all data acquisition and most control experiments in the course.

Other constraints on laboratory development relate to the specific equipment or experiments chosen. Any student laboratory equipment should be rugged. This is particularly important at Texas A&M where approximately 225 students take the required laboratory course each year. Since students can be quite tough on equipment, it is worth the additional expense to purchase high quality equipment. The selection of personal computers for the laboratory is a specific example. Several Texas Instruments Personal Computers were donated to the department for the laboratory. These machines are ruggedly constructed and have a keyboard with a steel chassis. When students accidentally drop equipment or vent their frustration on the keyboard, these well built machines weather abuse that damages the lower cost "clones".

The experiments should be versatile. The systems should be designed so that the parameters are easily modified. If a system is static, students are tempted to copy laboratory reports from previous semesters. To hold down equipment cost, the system should be designed so that several experiments demonstrating different concepts can be performed with the same basic hardware.

The equipment purchased for the laboratory need not necessarily be state of the art. For example, a number of system analyzers can automatically generate a frequency response curve for a given system. With an analyzer, the student takes little part in the analysis process. Remember that the goal is for the student to understand the phenomenon and not just to collect a specific set of data. Once a student has generated a frequency response spectrum manually, he may understand more fully the phenomenon and appreciate the use of a spectrum analyzer.

In addition to the other choices, one must decide whether to purchase the experimental equipment from commercial sources or to design and build the equipment "in-house". Most commercially available equipment comes with preplanned experiments and all of the necessary attachments, so its obvious advantage is that very little time need be spent planning and designing the experiment. The disadvantages of this approach are cost and applicability. Most commercial systems are designed to attract as large a market as possible and may not meet specific needs. Most commercially available experiments are expensive since development costs and profits must be amortized over relatively small number of units. Designing your own experiments offers exactly the opposite set of advantages and disadvantages. Usually the hardware costs of this equipment are much lower. Only basic components need be purchased if technician support is available to build and assemble the device. Also, the equipment can be designed to demonstrate specific concepts that reinforce class material. The disadvantage with this approach is that it is extremely time consuming to design these experiments. An experiment that effectively demonstrates a concept without being overly complicated or contrived can be a difficult design task. These devices must be prototyped and field tested to determine possible weaknesses before use in the laboratory, requiring significant investment of effort before the system may be used effectively.

In summary, the equipment and experiments chosen for a laboratory must be a trade off among many factors. When making the decisions, it is important to remember the basic reasons for having a laboratory and the specific goals for each experiment. These goals and the estimated number of students determine the approximate start-up costs for the laboratory. If the funding is below this minimum level, it may not be desirable to implement the laboratory until proper resources are available.

The following sections describe the equipment and experiments in the laboratory course at Texas A&M.

PENDULUM

Hardware Description

This setup is a single degree of freedom compound pendulum (Figure 1). The pivot axis of the pendulum is connected to a rotary potentiometer, which produces a signal that is proportional to the angular displacement of the pendulum. The pendulum arm is replaceable; different sizes and shapes of pendula are available.

Experiment 1: Use of Analog to Digital Converter and Modeling

This setup is used for an experiment that introduces the student to the fundamentals of digital data acquisition and reinforces lecture material on modeling. The students are provided a menu driven program which records and plots a voltage signal versus time. They use this program to record the voltage across the potentiometer in real time as the pendulum oscilates. During this exercise, the students perform the following tasks.

1. Determine the system resolution (degrees per bit) and calibrate the system by determining at least one reference point.

2. Select an appropriate sampling rate.

3. Modify the program on the personal computer to convert the voltage data to angular displacement and store the angle versus time data in a file for data analysis.

Outside the lab students model the pendulum and compute its natural frequency using its geometry and the measured weight. Then, using the plot of angle versus time, the students compare their predicted response with the actual motion of the pendulum. It is easily seen that frictional torque at the pivot and deviations in moment of inertia cause a significant difference between the actual and computed response. Students then determine values for friction torque and moment of inertia from the experimental results.

Discussion

The student becomes familiar with programming the personal computers, with the interface subroutines, and with the basics of data acquisition. Also, the fundamental concept of parameter identification is presented by requiring the students to compare the results of a model of a familiar system with experimental data and then modify their model.

ROTARY TABLE

Hardware Description

Figure 2 is a schematic for the rotary table system. The system consists of the rotary table, two power supplies, a power amplifier, the analog control logic circuit, and an adjustable voltage source to provide the system a step input. The input to the system is a voltage proportional to the desired rotation angle of the table. This voltage is supplied by the DAC output of the personal computer.

The control logic circuit compares the input voltage to the feedback voltage from the potentiometer on the rotary table shaft and produces a low power control signal that is sent to the power amplifier. The power amplifier has switch selectable voltage gains of 0.1, 1.0, and 10.0 and furnishes power (current) to the motor on the rotary table. The rotary table consists of a DC PM servo motor, a table (pure inertia), a gear reduction between the motor and the table, and a potentiometer attached to the shaft of the table. This pot provides the feedback signal to the control logic and closes the loop.

Experiment 1: Modeling and Parameter Identification

The objective of this experiment is to model the system and conduct experiments to determine the values of the parameters in the model. A proportional control logic is used. Before attending the lab, the students derive the equations of motion governing the system, determine the transfer function for each component in the system, construct a block diagram of the system, determine the system transfer function, and devise a method to experimentally determine the system parameters. At the beginning of the lab, various parameter identification methods are discussed. Although there are many unknown parameters in the model, the model is second order if motor armature inductance is neglected. Thus only three parameters are required to characterize the system: the natural frequency ω_n, the damping ratio ζ, and the proportionality constant between table angle and voltage across the pot. The response to a step input is recorded for three values of gain. The students are provided a program that prompts the user for the magnitude of the step input; sends the voltage out over the appropriate DAC channel; and samples, stores and plots both the feedback voltage from the potentiometer and the control voltage sent to the motor. The system parameters are identified based on the known model structure and the response to the step inputs. The effect of gain on stiffness, response time, and steady state error are also noted.

Experiment 2: Digital Control

In this experiment the student writes a digital computer program to implement the proportional control logic. This program then replaces the analog logic circuit. If the controller is fast compared to the plant , the performance of the digital controller is similar to that of the analog controller. As the response of the plant becomes faster (less inertia) or the speed of the controller becomes slower (programmed delays), the performance of the digital controller degrades until it becomes unstable. This vividly demonstrates the effect of sample rate on response for a digital controller.

Discussion

Experiment 1 reinforces lecture material on modeling of motors, gives a second parameter identification experience, and introduces the student to feedback control with the analog proportional controller. In experiment 2, the student learns the mechanics of implementing a digital controller without the distraction of designing the control logic. The model parameters and response speed can be varied easily by changing the inertia of the table. A nonlinearity is exhibited if the power amplifier saturates and cannot supply the commanded voltage and current. This demonstrates the fact that any real actuator is limited in the amount of power it can deliver; if the controller attempts to exceed this limit the (linear) model of the system and any analysis based on this model are invalid.

COUPLED TANKS

Hardware Description

The basic experimental system is supplied by Tech Quipment (Figure 3). It consists of the following components.

1. Two hold-up tanks with orifice 1 connecting tank 1 to tank 2 and orifice 2 draining tank 2.
2. A pump driven by a DC motor to fill tank 1.
3. Transducers to measure pump output, q_1, and tank levels h_1 and h_2.
4. Various power supplies, filters, overflow tanks, etc.

Flow between the tanks is through three holes, 3 cm above the base of the tank, with diameters of 1.27 cm, 0.95 cm and 0.635 cm. A smaller (bleed) hole of 0.317 cm diameter is at a height of 1.5 cm. These holes constitute orifice 1 in Figure 3. The size of the orifice (and hence the degree of coupling between the tanks) is varied by plugging and unplugging the holes with the stops. With all stops removed, the container can be considered as one big tank. With the three largest holes plugged, the remaining hole allows for a weak interaction between the fluid levels. The water in tank 2 drains out via an adjustable tap, and the entire assembly is mounted in a large tray, which is also the supply reservoir for the pump.

Water is pumped from the reservoir into the first tank by the variable speed, fixed displacement pump motor unit. The motor changes speed rapidly in response to changes in input voltage compared to the time required for the tank levels to change. Motor dynamics, therefore, can be neglected. It can be assumed that the motor changes speed instantly and that its speed increases with input voltage.

The coupled tank instrumentation consists of a direct reading flow meter and pressure transducers to measure the heads in the two tanks. The motor drive and signal processing is performed inside the instrumentation box. The pump/motor is controlled by a voltage applied to the pump drive socket. The depth sensor outputs are provided as a voltage.

Experiment 1: Modelling and Parameter Identification

The objectives of this experiment are to derive the mathematical model that governs the fluid levels in the two-tank system and to determine experimentally the numerical values of the parameters in the model. Since parameter identification can be done from steady state data, this experiment requires only visual readings of flow rate and fluid levels. Both a nonlinear model and a linearized model about a prescribed operating point are determined for flow as a function of head.

Experiment 2: Simulation

In this experiment, the student develops a digital computer simulation of the tanks and compares experimental transient response data to the transient response obtained from the simulation using the parameter values determined in experiment 1.

Experiment 3: Controller Design

The students design and implement a digital controller to control the head in the second tank to any desired level. Their grade is based on the performance of their controller and their analysis of the controller. They model the system, linearize their model about some operating point, synthesize a control logic, analyze the control logic, write the control program, calibrate the sensors and actuator, and test and tune the controller. The most successful controllers combine feed forward and proportional feedback control and provide semi-automatic calibration of sensors under program control. Students who develop a good simulation are always impressed by how quickly and accurately they can tune the controller off-line with the simulation.

Discussion

This series of experiments on modeling, parameter identification, simulation, and controller design lead the student through the necessary steps in designing a controller. After completing the control project, the students are acutely aware of the effects of transducer accuracy and sensitivity and actuator limitations and nonlinearities.

MOTORIZED CART

Hardware Description

This motorized cart rolls on linear ball bearings along a three foot long track (Figure 4). The cart is forced in either direction by a plastic chain connected to a DC servo motor through a gear reduction and a sprocket. The system is interfaced to a personal computer for implementation of several control algorithms. Instrumentation consists of a DC tachomoter on the motor shaft and a potentiometer on one of the sprocket shafts, which indicates cart position. The motor is driven by a linear amplifier that receives its input from the Digital to Analog Converter (DAC) on the computer. This setup is used for the following experiments.

Experiment 1: Velocity and Position Control

In this experiment, the students design a controller that might perform one of a number of tasks. The following tasks can be performed without modification to the equipment.

1. Velocity regulation: the cart simulates a conveyor that must move at a constant speed in the presence of varying loads. The loads can be weights placed on top of the cart, objects dragged along a high friction surface, or weights acted on by gravity and connected to the cart by a cable over a pulley.

2. Velocity Profile: the velocity of the cart must follow a predetermined velocity profile, such as a trapezoidal profile that is typical for loading/unloading applications.

3. Position control: only the final position of the cart along the track must be controlled. This requirement represents a typical Point To Point application that is commonly used in CNC drilling and inserting machines.

4. Position and Velocity control: the final position and the velocity of the cart along the path are controlled. This represents the requirement for a single axis controller in any contouring system.

In these experiments students model the system, decide on feedback devices, select an appropriate control algorithm, implement the controller, determine the controller gains, and evaluate the performance of their controller.

Experiment 2: Inverted Pendulum

The motorized cart hardware can be modified to study control of an inverted pendulum. This experiment, which demonstrates control about an unstable equilibrium, has proved to be very popular with the students. The goal is to maintain the vertical position of the pendulum without driving the cart beyond its range of motion. The students model the system, design a controller, demonstrate that the control concept is valid through a simulation program, and implement the controller on the hardware. The effect of nonlinearities are particularly apparent.

Experiment 3: Flexible Link Control

A flexible cantiliver beam, instrumented with strain gages at its root, is mounted vertically on top of the cart. The strain gage signal, indicating the deflection of the beam, is amplified and interfaced to the computer through an additional ADC. The purpose of this experiment is to develop a model describing the system and to construct a controller that positions the cart and damps out the beam oscillations. These requirements are analogous to positioning the hand of a flexible robot arm.

Discussion

Some of these control experiments are quite challenging. They have all been conducted as projects by undergraduate students and are being added to the laboratory in conjunction with a curriculum revision.

CONCLUSIONS

Based on students' response in course/faculty evaluation and faculty assessment of students' performance, the experiments described above enhance the learning process in this modeling and control course. One indicator of the effectiveness of the laboratory is that since it has been taught there has been a large increase in the number of students who register for the elective controls course.

All students benefit from the lab; those who are indifferent to the lecture part of the course but enthusiastic about the lab probably benefit the most since their performance would probably be poor in a lecture only format.

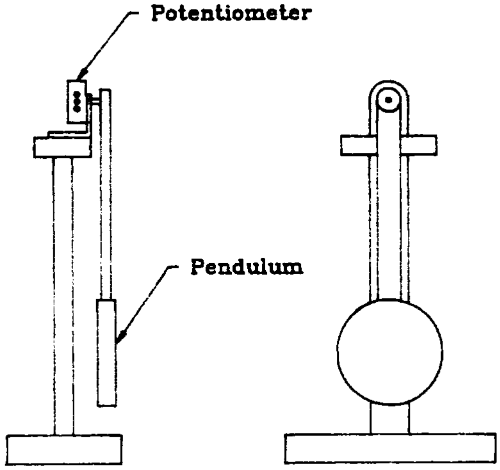

Figure 1 – Pendulum

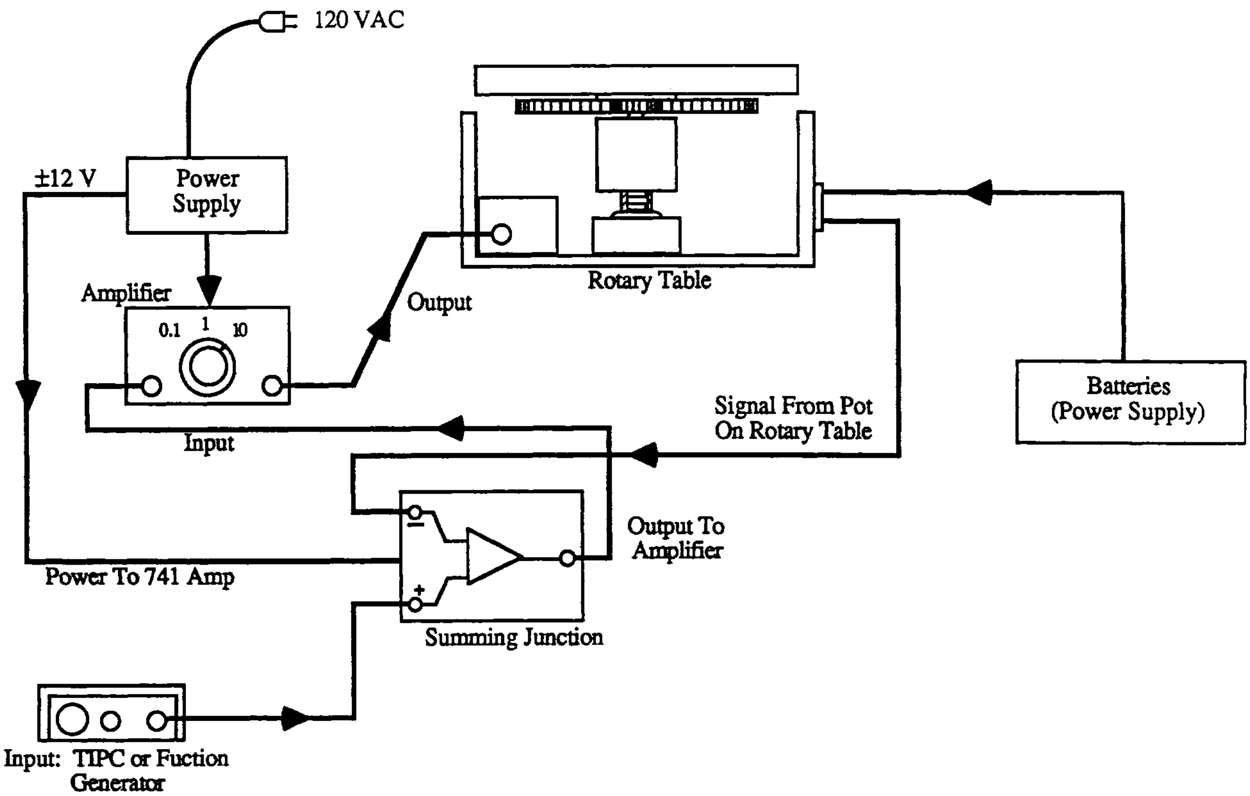

Figure 2. Rotary Table Control System Schematic

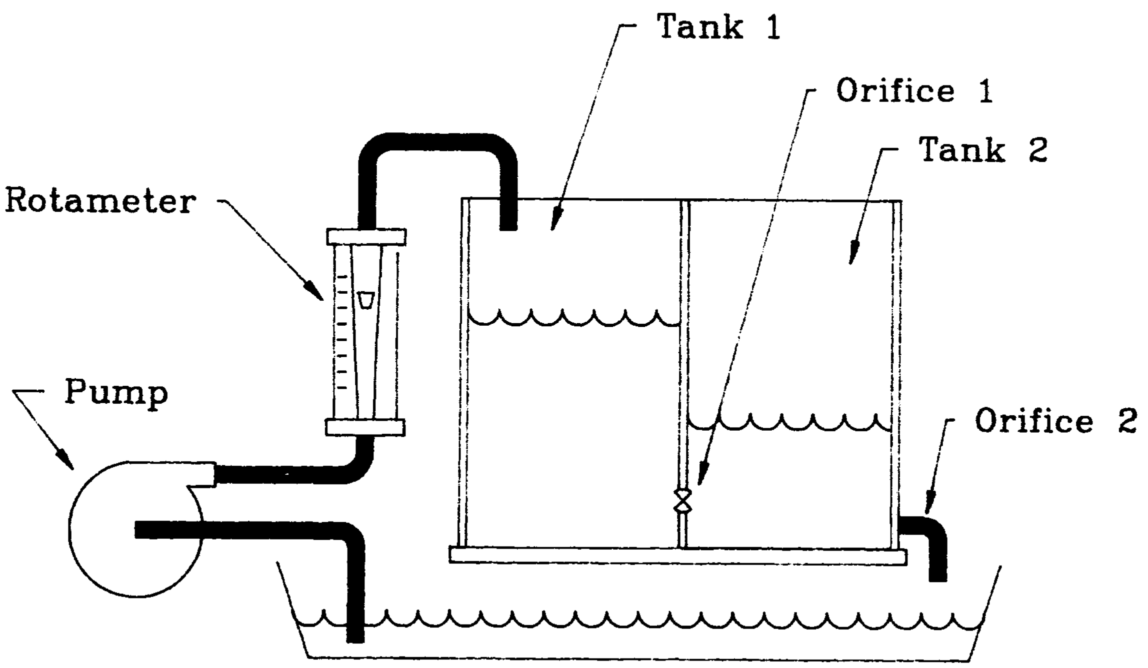

Figure 3 – Coupled Tanks

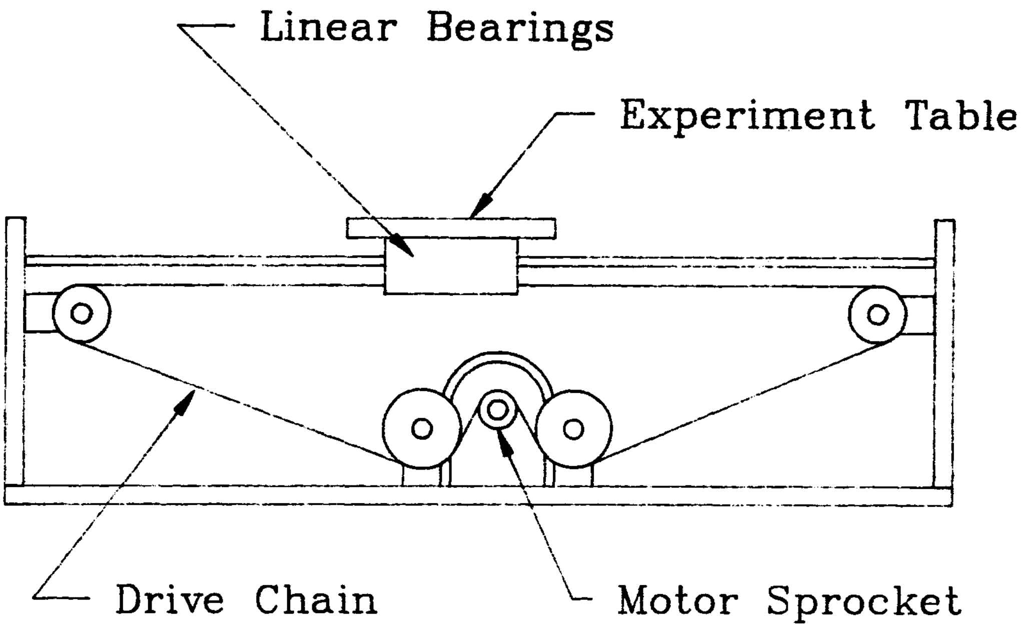

Figure 4 – Motorized Cart