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The Development of An Undergraduate Laboratory for Control System Design

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Abstract

An undergraduate laboratory for control system design at Texas A&M University consisting of eight experimental stations, each equipped with a computer and control system analysis and design software, interface hardware and software, and several physical plants that will be used for control experiments is described. Among these plants are: 1) a toy called Capsela, 2) a carousel, 3) a coupled tanks apparatus, 4) an electric train, 5) a robot arm, 6) a balance beam apparatus, and 7) an inverted pendulum apparatus. These plants cover a wide range of physical phenomena, and have different properties as far as control is concerned.

1 Introduction

Texas A&M University currently has approximately 1150 undergraduate students pursuing the Bachelor of Science degree in Electrical Engineering, which makes it one of the largest undergraduate programs in the United States. Among the courses presently required for all electrical engineering majors is a senior level course in feedback control. In recent years increasing numbers of undergraduate and graduate students from other engineering programs have also chosen to take this course and another elective course on digital control systems.

Examination of the topics covered in typical feedback control courses and textbooks indicates that the focus is on mathematical analysis. While this is necessary, we contend that it is very easy for the student to lose track of the goal: that is, to *control* some physical system by using some actual measurements. Although students gain facility in mathematical analysis, they lack the physical intuition on how to pose a control problem, how to model the system, how to determine which types of measurements are necessary and available, etc.. Beyond the cursory justification given to the feedback concept, little is done to illustrate, for example, the robustness of a well-designed control system, or the steps necessary in formulation of a suitable model for characterization of the system at hand. All too often, the student is "given" the block diagram and the transfer functions.

An undergraduate control systems laboratory consisting of eight experimental stations attempts to address this deficiency. Each station includes a microcomputer with analog/digital interface boards for data acquisition and for implementation of control. The computer is first used in the identification of a suitable model for the system, then as a design, simulation and display device using the Matlab CAD package, and finally as the actual implementation of the control law when interfaced with the physical system. For the purposes of the first course, the combination of A/D, computer, and D/A are treated as an analog controller $G_c(s)$. For the digital control course, the issues of sampling rate, digital control algorithms, finite word length, etc., can be investigated using the same equipment. And we are developing a control engineering and design course in which the students will study sensor and actuator devices and the integration of system components into a system using design tools and controller implementation tools such as Matlab, SIMULINK and Lab Windows. Seven "plants" which exhibit a wide range of physical phenomena give students experience in handling different types of problems, from a point that precedes the typical textbook setting, through to actual implementation and performance. We are also creating PC animation programs for each plant for students to test their design choice before actual implementation. The animation programs are also used to demonstrate instability phenomenon, which is usually difficult to demonstrate and potentially detrimental to the plant in the real implementation. By requiring the student to model and control a physical system, students gain a better understanding of the underlying theory; through their use of the CAD tools, they should be able to design better control systems, and be better prepared to face the demands of new technologies.

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2 Conceptual Design Facilities

For the CAD part, the following factors are deemed important: a) the software must be user friendly so that the students can concentrate on the design issues, b) the software must be flexible enough so that the students can develop their own subroutines if needed and, c) the price must reasonable. In addition, we decided to use the same digital computer that runs the CAD software as our "controller" for the physical plant. Our intent is to use fast enough sampling so that from the student's or plant's perspective the combination of A/D, computation, and D/A acts as the $G_c(s)$ that the student has designed.

Matlab is a high-performance interactive software package for scientific and engineering numeric computation. It integrates numerical analysis, matrix computation, signal processing, and graphics in an easy-to-use environment where problems and solutions are expressed just as they are written mathematically, without traditional programming.

We also use six optional toolboxes to extend the Matlab capabilities: (1) The Signal Processing Toolbox, which adds commands for one-dimensional and two-dimensional digital signal processing. (2) The Control System Toolbox, which includes commands for classical and state-space based analysis and design. (3) The System Identification Toolbox, which specializes in estimating models of a system based upon input-output data or on time-series. (4) The Robust-Control Toolbox, which includes functions for LQG/loop transfer recovery, H_2 and H_∞ control synthesis, and model reduction. (5) The Optimization Toolbox, for optimization of general linear and nonlinear functions. (6) μ-Analysis and Synthesis Toolbox for the analysis and design of robust control systems.

SIMULINK is a program for simulating dynamic systems. SIMULINK has two phases of use: model definition and model analysis. To facilitate model definition, SIMULINK adds a new class of windows called block diagram windows. In these windows, models are created and edited principally by mouse driven commands.

With Matlab, SIMULINK and toolboxes, students can: 1) identify the plant models through experiments. 2) simulate the dynamics of the different plants of system, study the effects of linearization, and obtain insight into the dynamic behavior of these plants. 3) work out the stability regions in terms of the controller parameters, search for an optimal controller. 4) compute the gain margin and the phase margin for the controller and the maximal allowable perturbation in the system model. 5) study the closed-loop system performance. 6) design state feedback controllers and dynamic observers.

3 Computers and Interfacing

As stated, PCs with data acquisition and control interface boards are used both for the design of controllers and for the implementation of the design. Four 80486-33Mhz PCs and four 80386-25Mhz PCs make up the experimental stations. Each computer has one 3.5 in. floppy drive(1.44Mbs), 100Mb hard disk, Mb memory, super GA color monitor with 1024 × 768 resolution. In addition, each 80486 computer has a 5.25 in. floppy drive(1.2Mb) and each 80386 computer has an 80387 math coprocessor.

3.1 Data Acquisition and Control Interface Boards and Their I/O Connectors

We use four Lab-PC boards, four PC-LPM-16 boards and eight CB-50 connectors as the interfaces between the PCs and the plants.

3.1.1 Lab-PC

The Lab-PC is a low-cost, multifunction analog, digital, and timing I/O board for PCs. The features of Lab-PC are:

- 12-bit ADC(with analog signal resolution of 2.44 mV at gain of 1. Finer resolutions down to 24.4 μV by using a higher gain.
  - -8 single-ended inputs
  - -Programmable gain of 1, 2, 5, 10, 20, 50, or 100
  - -62.5 khz maximum sustained sample rate
  - -Input range of 0 to 10 V or ±5V
  - -Counter/timers for A/D conversion timing and control
  - -16-word first-in-first-out(FIFO) A/D buffer to prevent data loss due to bus latency
  - -Internal or external A/D timing
- Two 12-bit, double-buffered DACs
  - -Unipolar and bipolar voltage output available
  - -Onboard timer for wave form generation
  - -Unipolar (0 to 10 V) or bipolar (-5 V to +5 V) output
- 24 digital I/O lines, configured as three 8-bit ports
  - -Software-configurable for input, output, or bi-directional transfers
  - -2 wire handshaking modes
  - -Interrupt generation
- 3 independent 16-bit counter/timers for frequency counting, event counting, and pulse output applications
- 8-bit DMA interface
- Programmed with Lab Windows software system or Measure

3.1.2 PC-LPM-16

The PC-LPM-16 is a low-cost multifunction I/O board for PCs. The features of PC-LPM-16 are listed below:

- 12-bit ADC
  - -16 multiplexed, single-ended inputs
  - -50 ksample/sec sustained sample rate
  - -Multiple-channel scanning
  - -Input ranges 0 to 10 V, ±5V, 0 to 5, or ±2.5 V
  - -Software-controlled calibration
  - -Timer for A/D conversion timing
  - -16-word-step first-in-first-out (FIFO) A/D buffer to prevent data loss due to service latency
  - -Interrupt generation
  - -Internal or external A/D conversion timing
- Low power consumption -120 mA at +5 VDC, 30 mA at +12 VDC
- 16 digital I/O lines configured as an 8-bit input and an 8-bit output port
- 2 independent 16-it counter/timers for frequency measurement event counting, and pulse output applications
  - -Interrupt generation on output of one counter
- Programmed with Lab Windows software

3.1.3 CB-50 Connector

CB-50 connector has 50 screw terminals. Cable terminates with 50-pin ribbon-cable connector.

3.2 Data Acquisition and Control Software

We use LabWindows and DOS LabDriver with the data acquisition and control boards to program our controllers and to display the state and control trajectories.

3.2.1 LabWindows

LabWindows combines standard programming languages with a development environment that simplifies programming data acquisition and instrument control systems. Students can use Microsoft C, Borland C and QuickBASIC to develop their control programs. They can interactively control the hardware in their system and automatically generate program code with the LabWindows function panel. They can easily analyze and display the results of their measurement and control operations. The LabWindows development system has extensive libraries of functions for data acquisition, data analysis, and data presentation, along with tools for editing and debugging user's programs.

3.2.2 DOS LabDriver

DOS LabDriver has high-level software modules for developing data acquisition applications. It is a sub-package of Lab Windows. It eliminates the low-level programming task and integrates the hardware capabilities with high-level application programming environment. Students can begin developing application software immediately. It is much cheaper than LabWindows.

4 Plants

We considered the following factors to enhance the hands-on experimentation: a) The controller implementation process must be simple and flexible enough so that students can implement wide varieties of designs such as classical designs through Bode diagram, PID, lead-lag compensation, etc., to more complicated modern designs such as state feedback using observers, adaptive controllers, neural controllers, fuzzy controllers, etc.. The process should also be able to be controlled by either analog (for the first course) or digital (for the second course) techniques. b) The experiment data should be easily stored, and be able to be extracted easily for analysis and display. c) The apparatus must be visually oriented so that the students can enhance their modeling and control concepts through visual observations. d) Each experiment should have its own distinct characteristics for modeling and control studies. e)The experiment apparatus must be robust enough so that it can be used for a long period of time without too much maintenance. f) The setup must be reasonably flexible so that it can be configured for different design issue studies. g) The apparatuses should include different sensors and actuators for our newly developed control engineering and design course. h) They must be reasonably priced.

We have constructed six plants on which to base the control experiments. These are the Capsela toy, a rotary carousel, coupled water tanks, a train, a robot arm, a balance beam apparatus and an inverted pendulum. The equipment, except for the Capsela and the balance beam apparatus, was designed and built in-house.

4.1 Capsela

We use a toy set called Capsela, as shown in Figure 1, to demonstrate elementary mechanical principles for electrical engineering students. Through a series of easy snap-together interlocking parts, each with its own special function, users can assemble a variety of motorized models. All moving gears and parts are visible through clear see-through capsules. Capsela is used for a quick review of basic mechanical and electrical principles. These simple experiments demonstrate fundamental electrical–mechanical interactions, force transformations and the role of controllers, and they will make the students realize the important role of sensors and actuators.

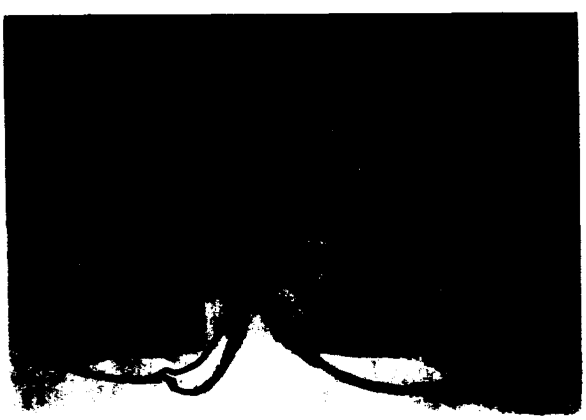

Figure 1: Capsela

4.2 Rotary Carousel

The rotary carousel, as shown in Figure 2, is driven by a stepping motor. The stepping motor can rotate in both directions and it is controlled by two TTL control signals: one for controlling its rotation speed, the other for changing its rotation direction. The rotary carousel can be used to demonstrate position control and speed control. It can also be used with a robot arm to simulate the operation of most simple indexing table assembly operations. It can be used in an elementary pick and place operation where the robot arm places a part on one position of the carousel, the carousel moves the part to another location and then the robot arm removes the part from the second location. We use the optical encoder as the digital transducer to feedback the position information. We shall demonstrate the response with and without feedback control loop, investigate the pulse skipping phenomenon and the feedback compensation techniques.

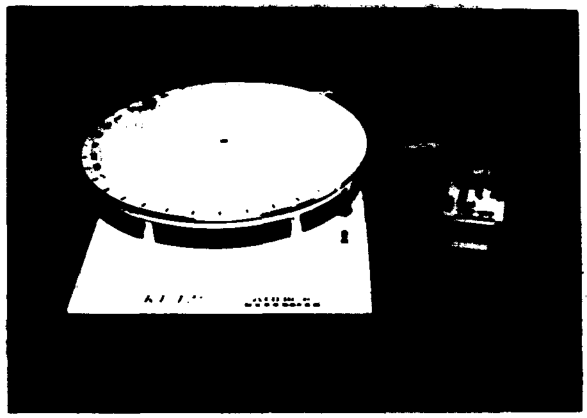

Figure 2: Rotary Carousel

4.3 Coupled Water Tanks

Coupled water tanks are shown in Figure 3. The situation is described by a coupled set of nonlinear differential equations. The dependent states are the fluid heights of the two tanks. The flow rate of the supply pump is controlled by a variable voltage power supply. Students interface to the apparatus by means of 4 tie points: (1) 5VDC. (2) ground. (3) An optical-isolated input for reservoir pump control, controlled by a TTL frequency over a range of 0 to 1KHz. (4) An optical-isolated output provides an indication of reservoir water level. The coupled water tanks can be used as a process control experiment prototype. For example, to control the flow rate of pump #2 for any unknow flow rate of pump #1 and any specified water level in the reservoir tank. The students will investigate the sensor response curve, the data acquisition interfacing using frequency and converted analog signals. The experiment can demonstrate the fundamental principles of PID controllers. For example, we can demonstrate the P controller may end up with a steady state error. The stability and instability of the system will be demonstrated. The calibration issues of the sensors will also be discussed.

4.4 Train

The train track has 12 Hall effect sensors mounted around the track, as shown in Figure 4. These sensors produce a pulse when the locomotive passes over it and the width of this pulse indicates the speed of the train at that point. The pulses from all sensors are combined to produce a single four bit output to represent the position of the train. The speed of the train is controlled by the student with a frequency applied to the "IN" terminal of the "student interface connector". The train can be used for position

Figure 3: Coupled Water Tanks

and speed control. For example, make the train go around the track, completing ten laps within a set time frame and stop on a certain sensor or make the train stop on sensor #5 on lap three for a predetermined time to let "traffic" cross the track, and then proceed at a speed to make up for lost time.

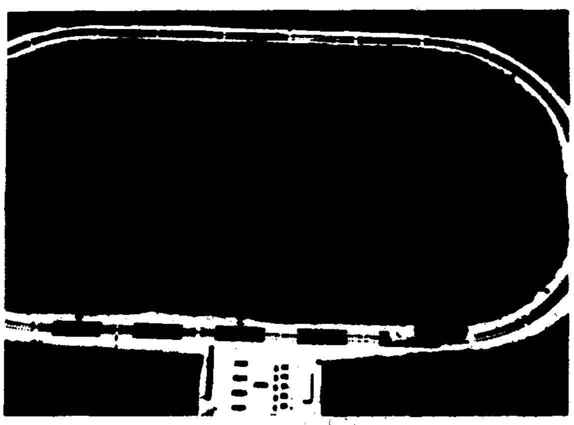

Figure 4: Train

4.5 Robot Arm

The robotics arm, TeachMover, is shown in Figure 5. Its possible motions include base rotation, shoulder bend, elbow bend, wrist pitch, and wrist roll, so it can simulate the motions of industrial units in production situations. The gripper can sense whether or not it is holding an object, and judge the size of that object within ±1/16 inch. The gripper has parallel jaws rather than pincers, which increases its versatility. Since the TeachMover operates at very low force levels, it is forgiving of operator programming errors. The robot arm can be used with a rotary carousel to simulate the operation of simple assembly operations. It can be used for demonstrating position and path control.

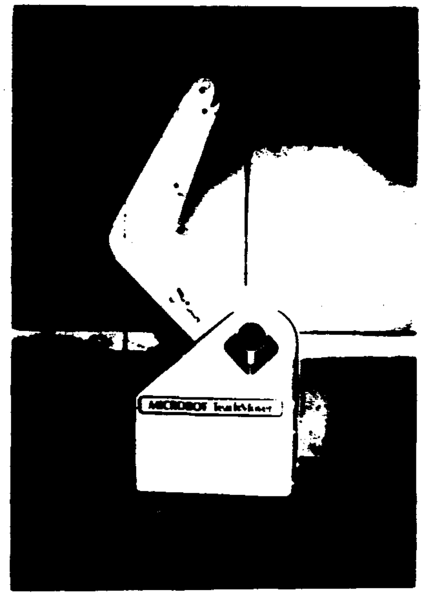

Figure 5: Robot Arm

4.6 Balance Beam Apparatus

The balance beam is an apparatus in which we use a potentiometer to measure the reel position and a tachometer to measure the angle velocity. The students will be first asked to design an observer to estimate the reel speed and the beam angle. Then the students will design an observer feedback to stabilize the reel at a desired position. The apparatus is nonlinear. When linearized, it demonstrates a non minimum phase unstable plants. The students can also investigate the nonlinear phenomenon, such as stability region, of the plant. For more advanced students, they can use Kalman filter and extended Kalman filter to investigate the regulator problems.

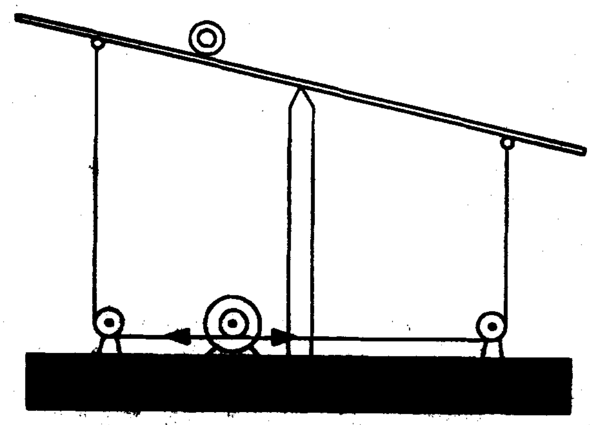

Figure 6: Balance Beam

4.7 Inverted Pendulum

We also intend to construct an inverted pendulum apparatus (schematic shown in Figure 6). It consists of a pendulum which is free to pivot on the carriage in a one-dimensional plane. The center of mass is above the axis of rotation. In this position, the system is unstable because any small perturbation will cause the pendulum to fall to its stable non-inverted position. The pendulum is stabilized in its inverted position by applying an appropriate force to the carriage. This force is determined by the controller and supplied by a DC motor or a stepping motor. The objectives of this experiment are to have the students understand and observe the phenomena of instability, and to have the students see how a stabilizing controller can make a difference in the system behavior. Again, the steps will be modeling, simulation, design of a controller, and implementation of the controller. However, consideration of issues on how to identify parameters for unstable systems and the impact of instability on numerical simulations will be emphasized.

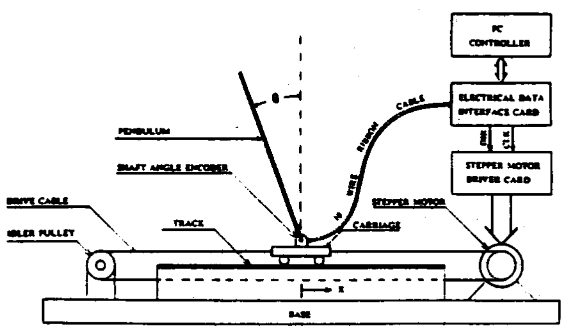

Figure 7: Inverted Pendulum

5 Experiments

5.1 Modeling:

The first issue is that of physical modeling. The mathematical descriptions of the plants will be presented in the lecture and the appropriate linearization will be derived. The students will be required to simulate, using Matlab, the dynamics of the plants, study the effects of linearization, and obtain insight into the dynamic behavior of these systems. For example, system identification will be performed with the student analyzing the step response. The relevant system parameters will be expressed in terms of measurable parameters such as rise time, settling time, and the percent overshoot.

5.2 Simple Control System Design:

The student will be required to implement a three parameter simple controller (PID) for position control. The effect of the different parameters on the system response will be investigated. The assignment will require that the students optimize the choice of the parameters for good system response. Using Matlab the students will be required to work out the robust stability regions in terms of the controller parameters. Within this region the search for an optimal controller will be done. This set of experiments will demonstrate clearly the use of feedback for servos, where the students can see how the error signals are processed by a simple three parameter control logic to generate a command signal.

Uncertainties in the modeling of physical systems will be analyzed and students can compute the gain margin (structured uncertainty) and the phase margin (unstructured uncertainty) for the controller. Also, the students will compute the maximal allowable perturbations in the system model before destabilization occurs. The students can verify the integrity of the controllers they design by perturbing the physical apparatus they are working with (e.g. by adding weights on the carousel, thus changing its inertial properties). For all the courses, except the control engineering and design course, the programming part is transparent to the students; and the students use the LabWindows created window menus to change their designed control parameters, such as PID gains or sampling rate, to evaluate the control performance. Accordingly, the students can concentrate on the control design issues rather than the implementation issues. The implemented issues will be studied in the newly developed control engineering and design course.

5.3 Frequency Domain and State Space Methods for Compensator Design:

Students will design classical controllers of the lead and lag type through the use of Bode and root locus plots in Matlab. In addition, state feedback controllers and dynamic observers can be designed using Matlab tools. System simulations illustrate the performance of the control systems prior to their implementation. Special issues (e.g. location of the closed-loop poles on the system performance) will be studied by simulations and experimentation. Comparisons between the performance of lead-lag compensators and observer-based compensators will be made.

5.4 Discretization Techniques:

Students who are enrolled in the digital control course can study the role of sampling rate and the various digital redesign or direct digital design techniques. Simulation experiments that demonstrate the difference between the continuous behavior, and the discrete equivalence will be done.

5.5 Sensing/Actuating Principles and Implementation Issues

In the newly developed control engineering and design course, the students will study the sensing and actuating principles, the response models of involved sensors, actuators and other system components. The students are also asked to use LabWindows to program and interface. Detailed system analysis and design will be carried out using Matlab and the associated tool box. Then the designed controller will be implemented using Borland C or Microsoft C in the Lab Windows environments. The interfacing and signal conditioning issues will be studied. Modelling errors and their impacts will be analyzed.

5.6 Senior Projects on More Advanced Control Techniques

The laboratory is also intended for senior students working on their senior projects. Control system design projects can be based on more advanced concepts from nonlinear control, adaptive control, or robust control.

6 Conclusion

The laboratory as described attempts to provide undergraduate students with a cost-effective hands-on experience combining theoretical analysis and hardware implementation techniques in the design of controllers on close-to-real-world plants.

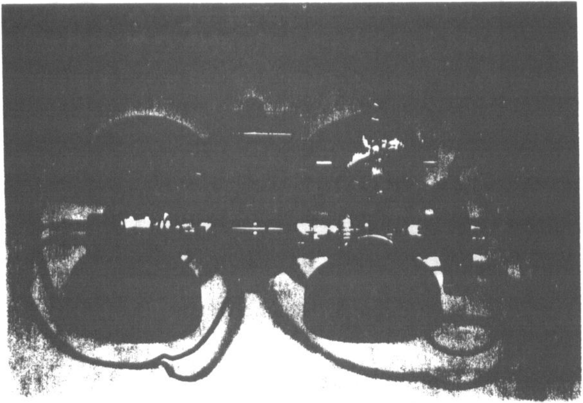

Figure 1: Capsela