A MODULAR CONTROL SYSTEMS LABORATORY

Martin T. Hagan and Carl D. Latino

Department of Electrical and Computer Engineering

Oklahoma State University

Stillwater, Oklahoma 74078

ABSTRACT

It is often difficult for students to visualize how control theory relates to real systems. Computer simulations can help, but simulations alone are limited by how well the system in question has been modeled. In general, simulations are more helpful to engineers with sufficient experience with real systems, than they are to students who may have never seen the actual systems in action. It is more enlightening if the results obtained theoretically are actually applied to a physical system. Applying the theoretically calculated results to a real system helps the student not only visualize, but evaluate how well the model was able to predict the system performance. To this end, a new interdisciplinary controls laboratory has been introduced jointly in the Electrical and Computer Engineering and Mechanical and Aerospace Engineering Departments of Oklahoma State University.

INTRODUCTION

The best way to learn about control systems is to design a controller, apply it to the system and then watch the system in operation. In controls classes, students learn to manipulate root locus diagrams, Bode plots, Nyquist diagrams, etc., but they often fail to relate these theoretical concepts to real-world problems. In an effort to bridge this gap, computer simulations are often used to assist students in visualizing systems. A system is modeled on a computer, and, with the help of graphics, the system can be seen in action. However, the system being observed in the simulation is in reality just a model of the true system. The model must always be a simplified representation of the system, and cannot reproduce all aspects of system behavior. Such effects as stiction, quantization, backlash, etc. are difficult to simulate, and are best understood from hands-on experience with the physical system. In addition, there are implementation considerations which are never addressed with computer simulations, such as interrupt programming and real-time executives.

To help bring these and other points across to the students, we have designed a modular controls laboratory. It utilizes the latest real-time computer and network technology to set up a flexible lab for students to more fully learn about control systems. The lab consists of five test benches, net-

worked to a number of workstations, supporting real-time computer aided software engineering (CASE) tools. Each lab station consists of an experimental apparatus, real time computer, a UNIX workstation, and associated software. Each of the experiments consists of an electro-mechanical system and associated computer interface card. Versions of some of these experiments are commercially available as stand alone units, which cost on the order of $15,000 each. Instead of purchasing them, the systems were designed and built by senior students in our capstone design class.

The experiments are all designed to be modular, interchangeable and VMEbus compatible. In addition, all of the experiments are designed so that masses, inertias, and other system parameters can be changed easily. This allows the same experiment to introduce new challenges each semester. The lab currently has five experiments, other experiments will be added periodically to broaden the types of problems undertaken. The experiments were chosen because they are inherently unstable, visually appealing, and technically challenging. These features have a positive effect on student motivation.

There are labs worldwide (Gill and Haas 1981; Steadman *et al* 1981; Tummala 1983; Hagan *et al* 1984; Franklin and Powell 1989; Ozguner 1989; Mansur and Schaufelberger 1989; Wellstead 1990; Astrom and Lundh 1992; Hsu 1992; Shoureshi 1992) which have some features in common with this lab. Many of the labs have two or three of the same experiments (e.g., Wellstead 1990; Astrom and Lundh 1992; Shoureshi 1992). A few make use of workstations, networking and VME bus systems (Astrom and Lundh 1992). However, there are several features which make our lab unique. First, the equipment is of the latest technology, using embedded rather than PC-based controllers. This is typical of the equipment that is used in industry, where embedded systems, rather than PC's, are used for real-time control. An industrial advisory board assists the authors in keeping track of industry trends. Also, all of our labs are designed and built to our specifications by students in our capstone design class. This provides a continual supply of projects for the design class, and enables us to have a large number of interesting experiments. In addition, the lab is equipped with state-of-the-art CASE tools to assist students in all phases of the design process.

In the next section of this paper we will explain the purpose of the lab, and will describe how it fits into our curriculum. Then we will discuss the organization of the laboratory and present some of the experiments.

PURPOSE OF THE LAB

This controls laboratory is used in a variety of ways:

- It is thoroughly incorporated in the senior elective course in automatic control systems.

- It provides, on a continuing basis, projects for the capstone design course.
- It is used extensively for demonstrations and brief experiments in a variety of other courses, and for exhibitions to departmental visitors, including prospective students.

Senior Control Systems Course

The main use of the laboratory is as part of the senior elective course in automatic control systems. Groups of three students each will be assigned to individual experimental systems. Each group performs a semester long design project which has the following milestones:

1) Mathematical modeling of the system
2) Computer simulation of the modeled system (using Matrix_X or MATLAB)
3) Verification of the mathematical model
4) Design of classical controllers (i.e. lead-lag or PID)
5) Computer simulation of the closed loop system
6) Software implementation of the controller and design modifications
7) Experimental testing of classical controller and design modifications
8) Design of state variable controller/observer
9) Simulation of closed loop system
10) Software implementation of state variable controller
11) Experimental testing of state variable controller and design modifications
12) Final Report

The design process is open-ended and self-paced. The students will have access to the laboratory at a variety of times, and all the design, simulation and software development can be done at many workstations located conveniently throughout the College of Engineering.

In the past, our senior controls course has required that the students complete a term project. It consisted of some mathematical modeling and control design, and it required computer simulation to verify, or suggest refinements to, the final design. This project was very helpful in giving students an overview of the design process. However, the paper design and simulation testing cannot provide students with all the intuitive insights and understanding of the practical considerations that the laboratory experience can bring. In addition, there is nothing as satisfying and confidence building as seeing your design work in real-life.

Some of the concepts that the students should learn from the lab, which cannot be adequately learned from paper designs are:

1) Real-time programming

2) Effects of sampling rate
3) Use of interrupts
4) Importance of maintaining correct units
5) Effects of disturbances and nonlinearities such as friction
6) The iterative process of design (the first design is often not best or may not even be functional)

Capstone Design Course

Another feature of the lab that makes it unique is the close association with the capstone design course. Each experimental system (including sensors and computer interface) are designed, built, tested and documented by a four-person project team. From our experience in constructing the existing lab setups, these control systems make ideal senior design projects. Construction began during the spring semester '92, when a team of four students in the capstone design course designed, built and successfully tested the Ball on Beam experiment (see the upper left diagram in Figure 2). This was the most popular project in the course (selected as first choice by more students at the beginning of the semester), and turned out to be the most successful project. Since each experimental system has a similar computer interface and overall concept, the completed project provided an excellent template for the ensuing designs. In the following four semesters, four more experimental systems were built. The plan is to add one or two systems each year for the foreseeable future.

Demonstrations/Presentations

A third important use of the laboratory is for demonstrations and brief experiments in a variety of other classes. For example, in the junior level linear systems class demonstrations are given to illustrate the concepts of transient response, feedback and stability. The lab is also used for demonstrations to freshmen and high school students who have interests in engineering.

EQUIPMENT

Basic Laboratory Setup

The controls laboratory consists of five lab stations. The laboratory layout is shown in Figure 1. At each of the five lab benches is a target system which includes a VME bus enclosure, power supply, a CPU card (Motorola 68040 processor) with ethernet interface and real-time kernel (VxWorks), the system I/O interface, and the experimental system. (The I/O card and the experimental systems are built by senior project design teams. The experimental systems are described in the next section.) The laboratory is equipped with five engineering workstations for computer simulation, software development and real-time system testing, and a printer for graphical output.

The entire lab is networked to a large number of other workstations within the College of Engineering. Software development can be done on any of these machines. In fact, the final software can be down-loaded to a work bench and run remotely from any networked machine. The only time someone needs to physically be in the laboratory is when the control system is active. This allows efficient use of the laboratory.

Most undergraduate laboratories use PC's for data acquisition and control. We decided against that option and instead chose our format for the following reasons:

1) The equipment is typical of industrial applications, with workstations and CASE tools for software development, and embedded computers for real-time control.
2) The system is modular, allowing simple upgrades when microprocessor technology becomes outdated.
3) Students learn to use real-time kernels (operating systems which have been customized and streamlined for real-time operation) to implement control algorithms.
4) The systems are networked, allowing simple access to many existing resources.

Complementary Facilities

The laboratory makes use of a significant amount of other hardware and software. First, the control laboratory is networked to all other workstations in the College of Engineering, including a large computer laboratory that is in the same building as the control lab. The computer lab contains seven Sun workstations, 17 IBM rs6000 workstations, three laser printers, 35 80486 PCs and four Macintosh IIci microcomputers. This computer lab is open seven days a week until 11 PM. The control lab is also networked to the Real-Time Distributed Systems Laboratory, located in an adjacent lab, which contains four Sun workstations, a VME system with seven processor cards with real-time kernels, and a laser printer.

There is a significant amount of existing software that is used by the laboratory. Matrix$_X$ and MAT-LAB are available on all workstations for control design and computer simulation. Real-time development tools (CADRE), and a C compiler, with necessary libraries and header files for the VxWorks real-time kernel, are available on the Sun workstations in the computer lab and the Real-Time Systems Lab, and have been ported to the new workstations. There is also a significant amount of real-time software and Xwindows graphical display software that has been developed on research projects during the last few years (Hagan *et al* 1988, 1990, 1994).
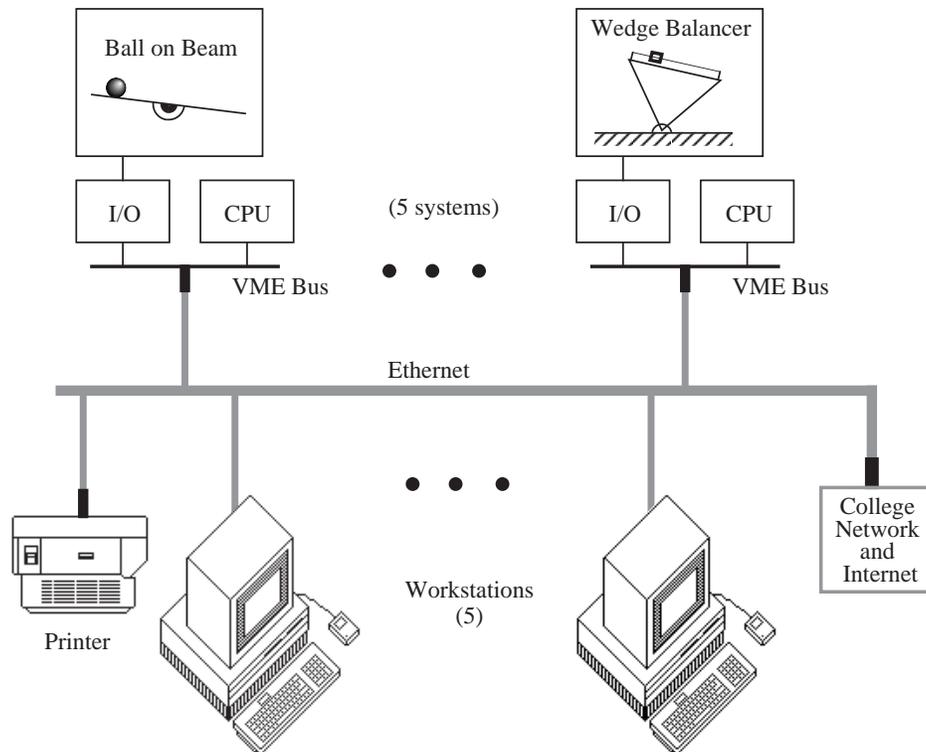
Figure 1. Laboratory Layout

EXPERIMENTAL SYSTEMS

The lab consists of five work benches, each containing a different experimental system to be controlled. The systems will be changed each semester as new setups are rotated through the laboratory. The experimental systems will be chosen based on four criteria. They must be 1) interesting, 2) visual, 3) instructive and 4) reasonably challenging. Figure 2 displays a set of 16 such systems that will be used as a starting point. (This set is representative but not complete.) Six of these systems have been completed so far. One or two systems will be added each year, for the foreseeable future. The purpose of continuing to rotate new systems into the lab is to keep the lab fresh and exciting, and to diminish the possibility of solutions to the experiments being passed down from one year to the next. In addition, the lab experiments provide excellent projects for the capstone design course.

The six experiments which have been completed so far are: the Ball on Beam, the Magnetically Levitated Sphere, the Cart and Pole, the Wedge Balancer, the Two-Link Pendulum, and the Inverted "T". Each of these systems was completed in a one-semester capstone design course by a four-person design team. These teams were required to design, build, test, and document: the mechanical hardware, sensors and actuators, computer interface, and real-time software.

For each system, the computer interface was implemented using the VME bus. For this reason the laboratory is very modular; any component of the laboratory setup can be used at any lab station. This will allow us to upgrade the laboratory as new computing technology becomes available.
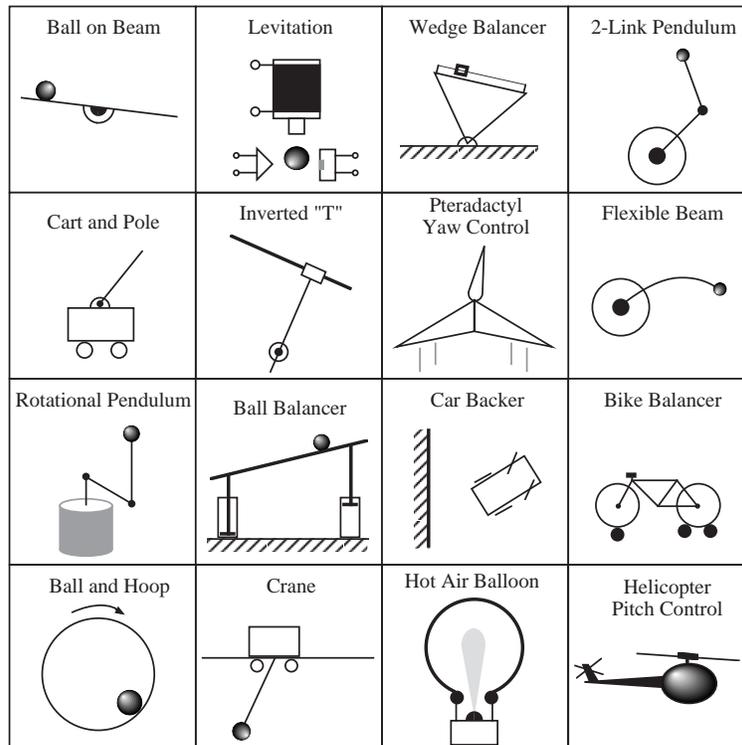

Figure 2. Experimental Systems

Figure 3 shows the Rotational Inverted Pendulum. It also illustrates how the experimental setup physically interfaces with the laboratory hardware. The system consists of a workstation (not shown), a Networking Computer (lowest card in the rack), a Control Computer (second card from bottom), an Interface Card (uppermost card with cable), and the electro-mechanical portion of the system. The mechanism and the motor drive circuit are enclosed in the plexiglas box on the right. A D.C. motor is directly connected to the first link of the pendulum. The second link rotates freely. Two optical encoders are used to measure the angles of the two links.

The workstation is connected to the experimental setup via the network. It is used to download programs and real-time commands into the Control Computer via the Networking Computer. The Control Computer has the responsibility of monitoring and controlling the Rotational Inverted Pendulum (or other experimental setup) via the custom interface card. All of the other systems are similar in construction, and are designed to interface with the Control Computers in a similar fashion. Each has its own custom interface card and is constructed of clear plexiglas, so that the inner workings are clearly visible.
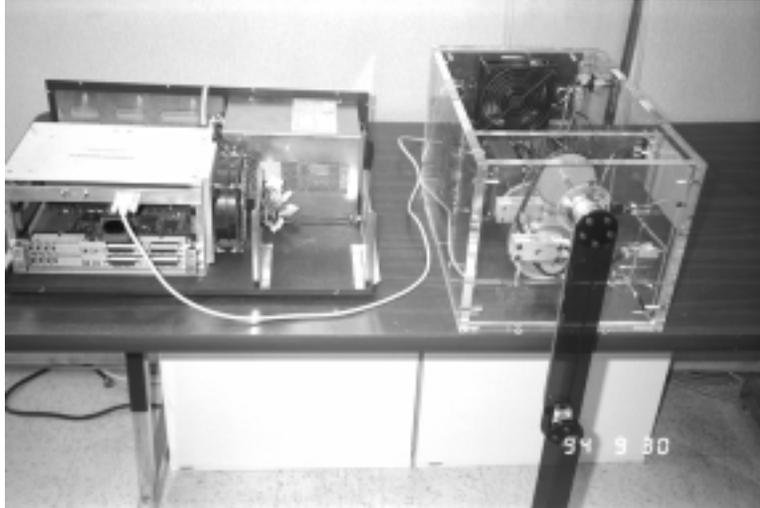
Figure 3. Two-Link Pendulum

Figure 4 is a photograph of the Wedge Balancer. A cart slides along a rack at the top of the wedge to bring the system into balance. Two optical encoders, one on the cart and one on the wedge, provide position information. The control algorithm then computes the appropriate voltage to be applied to the cart motor. The power supply and power amplifier are contained in the box behind the wedge, and the interface board is displayed in front of the wedge.
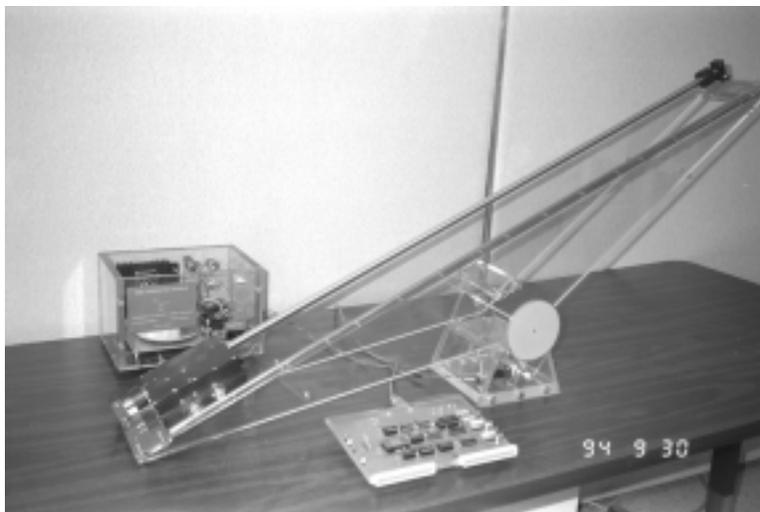

Figure 4. Wedge Balancer

Figure 5 displays the Ball on Beam experiment. A D.C. motor is used to turn a plexiglas beam, in order to position a ball which rolls along a grove in the top of the beam. The position of the ball is sensed by an ultrasonic transducer, and the beam position is sensed by an optical encoder. The power supply and power amplifier are contained at the back of the plexiglas box, which also contains the D.C. motor. The interface board is on the far side of the box.
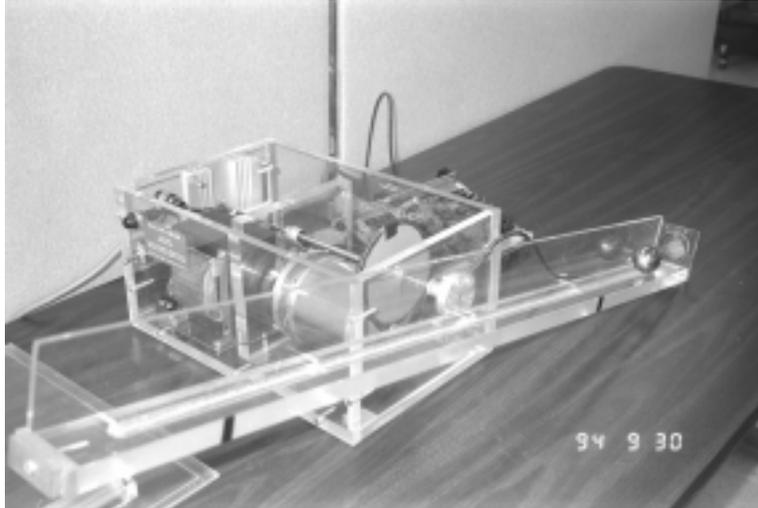
Figure 5. Ball-on-Beam Experiment

We have included photographs of some of the experiments to indicate the high quality of workmanship achieved by the capstone design project teams. All of the six experiments which have been completed so far are of the highest quality, and have been designed to last for many years. Each project was completed in one semester by a four-person design team. We had some initial concerns about the consistent quality of systems designed and built by the capstone design teams. We have been very pleased by the high quality of their work.

CONCLUSIONS

Students can obtain a good background in the theoretical aspects of control system design from lectures, textwork and computer simulations. However, there are many practical problems that cannot be easily understood without access to a physical system (e.g., sampling, quantization, real-time programming, interrupts). Without a laboratory experience students often end up with some unusual notions about how a control system design would actually be implemented. With laboratory experience students develop intuitive insights which complement their theoretical knowledge. In addition, when the experiments are visual and exciting, and the equipment is of the latest technology, the laboratory can motivate students to spend more time on classroom activities.

In this paper we have described a modular control systems laboratory to address these concerns. The key features of this lab are: it uses state-of-the-art embedded controller technology and real-time kernels; it has a large set of visually interesting and technically challenging experimental devices; the laboratory setups are highly modular and can be easily upgraded when the computer technology becomes outdated; the experimental systems are designed, built and tested by students in our capstone design course, which provides an excellent design experience for our students and

provides the department with significant savings in equipment costs; and the systems are net-worked, allowing easy access to many existing resources.

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REFERENCES

Astrom, K.J. and M. Lundh. 1992. "Lund control program combines theory with hands-on experience." *IEEE Control System Magazine*, vol. 12 (June), pp 22-30.

Franklin, G.F. and J.D. Powell. 1989. "Digital control laboratory courses," *IEEE Control System Magazine*, vol. 9 (April), pp 10-13.

Gill, D.B. and V.B. Haas. 1980. "Purdue's junior-level control laboratory with microprocessors." *IEEE Transactions on Education,* vol. E-24 (February).

Hagan, M.T. 1984. "A Microcomputer-controlled experiment: Root locus design," *IEEE Transactions on Education*, vol. E-27 (May) pp 79-85.

Hagan, M.T.; C.A. Hernandez; W.C. Yeung; and M. Hozhabri. 1984. "A control systems laboratory with microcomputer supervision," *IEEE Control System Magazine*, vol. 4 (February), pp 15-19.

Hagan, M.T.; C.D. Latino; N.M. Sammur; and J. Hamalainen. 1988. "A digital control loading workstation." *Simulators V*, Simulation Series Vol. 19, Number 4, Society for Computer Simulation, San Diego, California (October) pp 470-473.

Hagan, M.T.; N.M. Sammur; G. Guimaraes; and D. Schooley. 1990. "Digital motion for flight simulation." *Simulators VII*, Simulation Series Vol. 22, Number 2, Society for Computer Simulation, San Diego, California (April), pp 88-93.

Hagan, M.T.; N.M.Sammur; G. Guimaraes; C.D. Latino; and J. Hamalainen. 1994. "Distributed control loading and motion for flight simulation." *Progress in Simulation*, Vol. 2, Ablex Publishing.

Hsu, P. 1992. "Dynamics and control design project offers taste of real world." *IEEE Control System Magazine*, vol. 12 (June), pp 31-38.

Mansour, M. and W. Schaufelberger. 1989. "Software and laboratory experiments using computers in control education." *IEEE Control System Magazine*, vol. 9 (April), pp 19-24.

Ozguner, U. 1989. "Three-course control laboratory sequence," *IEEE Control System Magazine*, vol. 9 (April), pp 14-18.

Shoureshi, R. 1992. "A course on microprocessor-based control systems," *IEEE Control System*

Magazine, vol. 12 (June), pp 39-42.

Steadman, J.W.; R.G. Jacquot; and M.N. Hepworth. 1981 "A microprocessor system for the discrete-time control laboratory." *IEEE Transactions on Education,* vol. E-24 (February).

Tummala. R.L. 1983. "Control systems experiment: Use of microprocessors in introductory control laboratory," *IEEE Control System Magazine*, vol. 3 (February).

Wellstead, P.E. 1990. "Teaching control with laboratory scale models." *IEEE Transactions on Education*, vol. 33 (August), pp 285-290.