Session 2532

Providing an Updated Dynamic Systems and Controls Lab Experience

Bill Diong
The University of Texas at El Paso

Prologue

Both the undergraduate Electrical Engineering and Manufacturing Engineering curricula at the University of Texas - Pan American (with which the author was affiliated until recently) include a required course in Automatic Control (it is optional for Mechanical Engineering students). Up till now, they have been taught in a lecture-only format. But recently, in keeping with the newly developed mission statements for all three programs, it was decided that students in these (and other) courses be provided with relevant hands-on laboratory experience. However, this decision was made at a time when control systems engineering was, and still is, undergoing significant changes.

Firstly, a paradigm shift is occurring with regard to the type of engineering graduates needed by today's fast-paced and intensively competitive global economy; employers want graduates with broader focus who can contribute almost immediately. Secondly, the price to performance ratio of computing power is rapidly decreasing resulting in greater and more diverse use of microcontrollers, digital signal processors (DSPs) and microprocessors. In response to these changes, we felt that these courses needed to prepare students to be more multidisciplinary in their thinking, to familiarize them with a model-based, simulation-oriented approach to control systems design and development, and also to provide them with experience in implementing DSP-based controllers.

Last year, a proposal to achieve these goals resulted in an Instrumentation and Laboratory Improvement grant from the National Science Foundation. We had proposed, firstly, that the students work with electromechanical systems to encourage multidisciplinary thinking. Secondly, that they needed to become adept at using common (in industry) software packages for system modeling, analysis, control design and simulation. Thirdly, that the students must learn how to use common (in industry) measurement instruments and techniques for frequency-domain modeling, analysis and control design purposes. Fourthly, that they needed to experience using a DSP development system to implement the control algorithms designed for the given electromechanical systems.

This paper details the objectives, tasks and accomplishments of this project. It will also provide preliminary findings on how this project has impacted student learning for the two Automatic Control courses. Last but not least, it will include ideas on how similar projects could improve on this present one.

I. Introduction

The University of Texas - Pan American (UTPA) is a comprehensive four year state-supported and public co-educational institution that is located in the city of Edinburg, Texas, about 20 miles north of the US-Mexico border and almost 60 miles east of Brownsville, Texas. When the institution joined the University of Texas system in 1989, its Board of Regents set a goal for UTPA to build a quality engineering program that would offer Bachelor's degrees in Electrical, Mechanical and Manufacturing Engineering. The pre-engineering program started in the fall of 1989 with 72 students. By April 1992, when the Texas Higher Education Coordinating Board gave its approval to the undergraduate programs to award degrees in those three disciplines, engineering enrollment at UTPA was 320. The three programs were accredited by ABET in 1997 and the enrollment currently stands at just over 600 students with an expected growth rate of about 7% per year for the next several years.

About 87% of UTPA's engineering students are Hispanic. A majority of them are also first generation college students from humble backgrounds. A significant minority work at least part-time, outside the university, to support themselves and their families. Compounding this challenging situation is a liberal admission policy that has resulted in classes with students spanning a wide range of ability and preparation. Many of them show a lack of confidence in their abilities and find it difficult to relate lecture material to real-world problems, especially in courses that tend to be more mathematically intensive. On the other hand, they appear more motivated and do better in our existing laboratory courses and in courses that use computers for solving problems, i.e., they enjoy hands-on experience and learn better that way.

The Engineering Department has plans to introduce a laboratory component to several existing courses in all 3 programs, but in particular, the Automatic Control courses that are required by both the Electrical Engineering and Manufacturing Engineering curricula. We felt that establishing a Dynamic Systems and Controls Laboratory will help greatly to stimulate the students' interest, boost their self-confidence, improve their understanding of the lecture material and prepare them better for a rewarding engineering career.

To achieve this, a proposal was recently submitted by the author and 2 other faculty members to the National Science Foundation's Instrumentation and Laboratory Improvement Program for the establishment of a state-of-the-art Dynamic Systems and Controls instructional laboratory at UTPA. The proposal was funded and this laboratory is now being developed for use (to varying degrees) by all Electrical, Mechanical and Manufacturing Engineering undergraduate students at UTPA. Its main goals are to:

a. prepare students to be multidisciplinary in their thinking
b. introduce students to a model-based simulation-oriented approach to control systems design and development
c. let students gain experience with the actual equipment needed for digital signal processor (DSP)-based controller implementation, and
d. allow students to demonstrate their implemented controllers on both educational and industrial hardware.

II. Laboratory Equipment: Hardware and Software

The key requirement driving the laboratory setup to service the various courses that will benefit from this lab (see below) is to have an open, integrated controller development platform that allows plant modeling, analysis, control design, system simulation, controller implementation and control verification. Such a platform has emerged only recently because of the tremendous gains in DSP technology and a simultaneous reduction in its cost. Furthermore, it is becoming widely adopted in industry as product development time and cost become more pressing concerns in an increasingly competitive global marketplace. Hence, we believe that the laboratory will not only serve as a means of education but also as a place of training to prepare our students to quickly contribute to their new employers.

The Dynamic Systems and Controls laboratory is equipped with the following:

a. Matlab, Control System and Symbolic Math toolboxes, Simulink and Real-Time Workshop
b. DSP development systems with motion control daughterboards
c. dual-channel dynamic signal analyzers/function generators /oscilloscopes
d. Inverted Pendulum systems, Torsion-Disk systems, Spring-Mass-Damper systems and Industrial Emulator systems
e. DC motors with amplifiers and encoders, and power supplies

Matlab, a product of The MathWorks Inc., represents the software platform underpinning the functions of almost all other equipment in the laboratory. It interfaces with a measurement and analysis module (described below) to provide visualization of the data acquired by the module. It is also used for system modeling, analysis, control design, simulation, and to provide an interface to a DSP control development system (also described below). This configuration allows one to graphically put together a model of the control algorithm, generate DSP code using that model and then download that code to the DSP. The software is available, for educational purposes, at a substantial discount. The alternatives to Matlab that were considered were ISI's MATRIX_X and Boeing's EASY5; however these are not as widely adopted or as broadly supported by third-parties as Matlab is.

The TMS320 DSP control development system with motion control board represents the cornerstone of all hardware in the laboratory. It is used to generate code implementing the desired control algorithms for the various plant systems for download to the DSP, and to provide the actual control signals for driving those plants. When compared with similar systems, e.g., the Spectrum C30 System or the ASPI Banshee System, the MX31 system from Integrated Motions Inc. is about 30% cheaper. At the time of writing, the other systems also did not offer a direct interface to Matlab, so that system-specific Matlab functions would need to be written to ensure proper DSP code generation.

The equipment in the laboratory also includes the SigLab 20-22 measurement and analysis module from DSP Technology Inc. which, with the aid of Matlab, implements the following instruments with graphical user interfaces: swept-sine analyzer, oscilloscope, function generator, spectrum analyzer, network analyzer and lattice system identifier. It provides all of the basic measurement and signal generation functions required for this laboratory in a single, small, portable and inexpensive package. While other monolithic-type instruments were considered, e.g., the HP 35665A dynamic signal analyzer, they were considered too expensive to have one each per laboratory station and had substantial capabilities that would rarely be utilized in an undergraduate laboratory, and so were dropped from consideration.

Various plant systems were evaluated. The vendors included Feedback Inc., Quanser Consulting and Educational Control Products (ECP). The systems need to be easy, and robust enough, for the students to work with yet present fairly challenging control problems with visible results. We finally selected 4 different ECP systems - Inverted Pendulum, Torsion/Disk, Spring/Mass/Damper and Industrial Emulator; these systems are also being used by many other leading institutions for teaching control systems principles. The inverted pendulum system with a DC servomotor is the main plant system for this laboratory as it satisfies all the above requirements. The other systems possess unique characteristics that provide a more enriching control education experience for the students. In particular, the industrial emulator model is ideal for teaching practical control of modern equipment such as spindle drives, turntables, conveyors, machine tools and automated manufacturing machinery. Its adjustable dynamic parameters and ability to introduce or remove nonideal properties in a controlled manner make it a perfect selection for industrial servo control training. We considered, but decided against, ordering these systems with their own controllers. Firstly, with the cost savings obtained we could buy more and different kinds of plant systems to be controlled by a common DSP control platform. Secondly, from a flexibility standpoint, one vendor did not provide an open control architecture, while another had an open control architecture but it was one that required programming in a C-like programming language rather than standard ANSI C. In contrast, the proposed approach using Matlab-based code development for the DSP controller requires minimal programming, yet is completely open.

DC motors are also part of this lab as they are simple systems to model and control (as a stand-alone unit). However, they will also serve as the actuators for the linkage mechanisms described below for MECE 3380.

The computers in this laboratory include 8 Pentium Pro PCs that were recently donated by Intel. The department provided funds for the monitors and the printers in this lab.

Figure 1 shows the hardware configuration for each station in this laboratory.

III. Impact on UTPA's Engineering program

Our plan to motivate students in their study of engineering, to prepare them to be more multidisciplinary in their thinking, to familiarize them with a model-based, simulation-oriented approach to control systems design and development, and also to provide them with experience in implementing DSP-based controllers revolves around the following proposed demonstrations and experiments. They are organized according to the course under which they will be carried out. Note that most of the courses for which experiments are being proposed do not presently have a lab credit, so the plan under consideration is to convert 1 hour of lecture credit to 1 hour of lab credit with part of the scheduled lab time devoted to lecture material experiment.

Demonstrations

ENGR 1101 - Introduction to Engineering : This is a required course that serves to introduce freshman and sophomore students to the fundamentals of engineering. Demonstrations of various control experiments should prove to stimulate the students' interest in the study of engineering as a means of understanding and solving real-world technical problems. It also represents an opportunity to introduce the students to the idea that present-day engineers need to be multidisciplinary in their thinking.

ENGR 2304 - Dynamics and ENGR 2405 - Mechanics : Both of these required courses have the goal of introducing sophomore-level students to Newtonian and energy-based dynamics. Physical demonstrations of controlled mechanical system motion will be extremely beneficial for the students, not only for visualization of the geometric aspects of constrained rigid-body motion but also in underscoring the criticality of the content of these courses with regard to mechanical/dynamic system design and implementation. The demonstrations planned for these classes would involve motion-control of gear trains, inverted pendulums and simple linkages. This represents an opportunity to introduce the students to the idea of electronic systems interacting with mechanical systems.

Experiments

ENGR 4461 & 4462 - Senior design I & II : A major goal of these courses is to develop a vehicle for the realization of the complete integrated process of system conception, design, fabrication, and operation. This process requires an interdisciplinary approach involving aspects traditionally housed in each of the three areas of Electrical, Mechanical and Manufacturing Engineering. We intend to introduce year-long projects involving students from each of the three disciplines in which the group will be faced with the conceptualization, design, fabrication (including component selection, as well as, manufacture), and implementation (including controller design - both hardware and software) of a device to satisfy a specified task. This type of activity will require students of different engineering disciplines to interact - and learn from each other, and require them to communicate/respond to faculty from areas other than their own and, hence, learn more about the other disciplines.

ELEE 4308 - Electromechanical systems : This course introduces the students to the concepts of AC and DC machines and their operation. The lab's equipment can be used for studies on speed and torque control of DC motors, which will complement similar experiments using the induction machines currently available in the department.

ELEE 4321 - Automatic control : This is the required introductory controls course for electrical engineering students. We plan to complement the existing lectures with laboratory experiences related to the following concepts:

a. frequency domain modeling
b. transient performance and steady-state performance
c. Bode plots for stability analysis and controller design
d. evaluation of various controllers for the inverted pendulum system (in default configuration) with introduction to the DSP development system and control implementation

e. modeling, analysis, control design, simulation and DSP controller implementation for the inverted pendulum system (configured differently from above) or another plant system

MANE 4321 - Automation systems : The course presently relies on example problems to demonstrate the impact of control on system stability and performance. The laboratory will provide the students hands-on experience to model different mechanical, electrical, thermal and fluid systems, and to design compensators to reinforce the concepts learned in lecture. Laboratory experiments for this class will run parallel to the lecture material covered and include:

a. system modeling of components - torsional mechanism, rectilinear mechanism
b. modeling of integrated systems - industrial emulator/servo trainer
c. time response studies
d. studies on the effect of gear ratio, inertia, friction, backlash and sampling period
e. design of compensators and performance evaluation
f. system identification via frequency response methods
g. controller design for an inverted pendulum system

MANE 4401 - Robotics : The purposes of this course are, first, to develop analytic approaches for the kinematic and dynamic modeling of robotic manipulators. Second, to develop various position, velocity, torque, and compliance (force/motion) control schemes as required by differing automation tasks. The experiments pertinent to this class are:

a. pick and place
b. peg insertion/assembly
c. trajectory control
d. disturbance force rejection
e. surface following (e.g., sanding, deburring, polishing, etc.)

MECE 3380 - Theory of machines : This required course has a three-fold purpose. Firstly, to introduce students to both historically and currently employed basic motion and force transfer devices, such as gear trains, friction drives and elementary mechanisms including 4- and 6-Bar linkages. Secondly, to introduce specific task-based dimensional synthesis/design approaches for mechanisms with an emphasis in the areas of gearing and 4-Bar linkages. Lastly, to introduce various Newtonian and energy-based methods for dynamic modeling and analysis of (primarily one degree-of-freedom) linkages. The following experiments/demonstrations will be carried out in this class:

a. verification of force analysis, shaking force and moment balancing of linkages

For a given/specified motion of a linkage, analytically determine (via Matlab) the bearing forces and the "shaking" forces and moments transmitted/applied to the foundation of the "modeled" mechanism, then

(i) experimentally determine said forces and moments via the controlled motion and measurement (using accelerometers) of the actual linkage

(ii) add masses as analytically predicted for "shaking" force, and then "shaking" moment, balancing and experimentally measure the results

b. dynamic model verification

(i) For a given motion of a linkage, analytically determine (using Matlab) the motor torque required to drive the linkage as specified, and verify experimentally via current/torque measurement.

(ii) For a given initial condition and known/specified applied input torque, predict (using Matlab) the resulting motion of a linkage, and verify experimentally via velocity/displacement measurement.

IV. Progress of Laboratory Development

The initial focus of this laboratory's development is to make it ready for use by the EE and MANE/ME Automatic Control students. At of December 1998, the following have been accomplished:

a. all of the required software and hardware has been purchased
b. the procedure for the frequency domain measurement and modeling experiment (on an RLC circuit) has been completed and a demonstration has been conducted for one class each of EE and MANE/ME Automatic Control students
c. control algorithms for one of the 4 mechanisms, the inverted pendulum, have been implemented on DSP and tested successfully
d. the procedure for the transient response experiment (PD control of the inverted pendulum) has been completed and a demonstration has been conducted for one class each of EE and MANE/ME Automatic Control students
e. the procedure for introduction to the DSP development system and control implementation has been completed
f. a Web site[1] to disseminate information about the laboratory, with text, pictures and movies, has been constructed and is now accessible to the public
g. two presentations/publications about this laboratory, describing its concept and one of its development phases, have been made[2, 3]
h. a survey of both EE and MANE/ME Automatic Control students has been performed to evaluate the current state of the project; its results are provided and discussed below.

The remaining tasks that need to be accomplished by July 1999 include

a. DSP implementation of the control algorithms for the other 3 mechanisms and testing them
b. completing the procedures for the other experiments to be conducted in the Automatic Control courses
c. putting all experimental procedures on the laboratory's Web site
d. completing the procedures for those demonstrations and experiments that have been proposed for the other courses
e. writing a final report on the project

V. Evaluation

Our plan for evaluating this project, after it is fully completed, will emphasize surveying the students on whether their laboratory experiences helped increase their interest in the courses and engineering in general, as well as their understanding of specific course lecture material. Additionally, feedback will be solicited via the laboratory's Web site.

As a preliminary effort, a written survey of the students taking the EE Automatic Control class (10 students surveyed) and students taking the MANE/ME Automatic Control class (13 students surveyed), who sat through two demonstrations each, was conducted recently. All of the students taking those classes are Hispanic. No specific background information is known about those students except that 5 of the students who took the survey are female. A more complete (and better-devised) survey will be administered after the students in these courses have been given the opportunity to perform the entire series of planned experiments.

The students were asked to respond (anonymously) to the following questions:

a. How much difficulty do you have grasping the concepts in this class ?
35% answered 'Slight', 39% answered 'Average' and 13% answered 'Quite a lot'

b. Have lab <u>demonstrations</u>, e.g., on frequency response measurement, helped your understanding of what is taught ?
17% answered 'Slight', 30% answered 'Average', 43% answered 'Quite a lot' and 10% answered 'Extremely helpful'

c. How much do you think lab <u>experiments</u> will help your understanding of what is taught ?
17% answered 'Average', 39% answered 'Quite a lot' and 39% answered 'Extremely helpful'

d. How much would you be willing to pay as lab fees to support a lab for conducting Controls experiments ?
39% answered '$15', 39% answered '$25', 4% answered '$35' and 9% answered '$45'

It was noteworthy that those students expressing greater difficulty grasping the concepts in lectures were more likely to answer that the demonstrations and proposed experiments were, and would be, beneficial.

VI. Dissemination

We hope to publish the final results of this project that includes a more detailed evaluation of its impact in an appropriate journal so as to more broadly disseminate the information about this laboratory's purpose, concept and implementation. Furthermore, the laboratory's Web site, which presently contains some information about the various experiments, pictures and descriptions of the different laboratory equipment and QuickTime movies of selected control experiments, will be regularly updated and continued to be made accessible to the public. In addition, we intend to provide demonstrations of the laboratory's capabilities during Engineering Open House and student recruitment visits to campus, as well as to show videotapes of our undergraduates performing the control experiments during off-campus student recruiting visits.

VII. Conclusions

From the results of the preliminary survey, we can conclude that the establishment of a Dynamic Systems and Controls Laboratory at UTPA has been, and will be, helpful for improving student learning in the Automatic Control courses. We strongly believe that it will also benefit students in other courses by stimulating their interest in the study of engineering and improving their understanding of the lecture material.

However, it has been a major challenge for faculty to devote sufficient time to this effort, since no released time was provided for by either the University or the Instrumentation and Laboratory Improvement grant. The present Course, Curriculum and Laboratory Improvement program of the National Science Foundation with its revised budget guidelines is therefore a welcome improvement in this regard.

Acknowledgments

This work is partially supported by the National Science Foundation through grant number DUE-9750757 under its Division of Undergraduate Education's Instrumentation and Laboratory Improvement program.

Bibliography
1. URL: http://www.engr.panam.edu/~dsclab/
2. Diong, B., Bose, S., & Freeman, R., "Updating the undergraduate Control Systems lab experience," *Proc. ASEE Gulf Southwest Conf.*, San Antonio, TX, Feb 1996.
3. Rodriguez, H., Ramirez, P., and Diong, B., "Modeling, simulation and control of a DSP-based inverted pendulum system," *Proc. ASEE Gulf Southwest Conf.*, Houston, TX, Mar 1997.

BILL DIONG
Bill Diong is currently an Assistant Professor in the Department of Electrical and Computer Engineering at The University of Texas at El Paso where he is developing an improved Dynamic Systems and Controls laboratory to be used by both Electrical and Mechanical Engineering undergraduate students. He received his B.S., M.S. and Ph.D. degrees from the University of Illinois (Urbana-Champaign), then proceeded to gain invaluable practical experience working as a Senior Research Engineer for Sundstrand Aerospace before joining The University of Texas – Pan American in 1995.

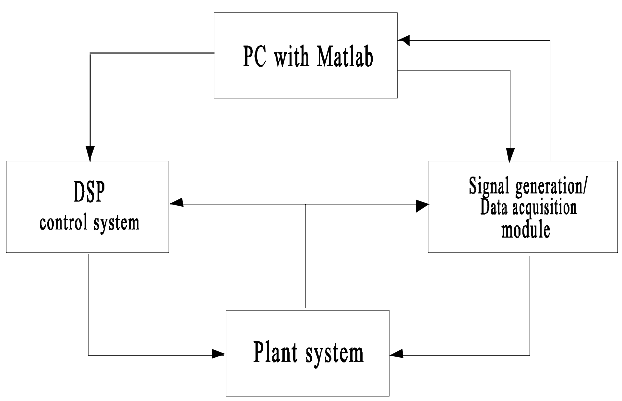

Figure 1 - Dynamic Systems and Controls laboratory station configuration