# A Collegewide Laboratory–Based Program in Control Systems Technology at The University of Illinois at Urbana–Champaign

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**Abstract**

We are developing a network of laboratories to support undergraduate and graduate education in Control Systems Technology in the College of Engineering at the University of Illinois at Urbana–Champaign. The cornerstone of our program is a centralized Core Laboratory, *The College of Engineering Control Systems Laboratory*, which provides basic instruction in feedback control systems to all Departments in the College of Engineering. This core laboratory feeds into a network of satellite laboratories, which are designed to provide both vertical and horizontal integration of control systems and related technology across departmental boundaries in the engineering curriculum. By elevating control systems laboratory development from the Department level to the College level we have gained a number of advantages including, more efficient use of space and equipment, better leveraging of funds, elimination of overlap among individual departmental labs, better integration of control systems technology in the curriculum, the ability to hire a full time professional to manage the laboratory, and increased visibility with industry. At the same time we retain the integrity and autonomy of the separate Departmental curricula. This paper describes our concept and our initial experiences in this laboratory development. We focus here on the description of the Core Laboratory while briefly describing the first group of satellite laboratories under development.

## 1 The Problem

Because of the interdisciplinary nature of control systems technology, most universities in the United States offer undergraduate courses in feedback control systems simultaneously in several different departments and many departments offer additional related courses in real–time systems, computer interfacing, robotics, mechatronics, and manufacturing automation. The central problems that we are facing and which are faced by every engineering school are:

1) How to provide high quality laboratory instruction in control systems technology without duplicating, or more likely diluting, resources across departmental boundaries, and

2) How to provide integration of the fundamental concepts of feedback and the systems approach to engineering design, within and among different engineering curricula.

The obvious answer of sharing resources among departments is not easily accomplished, primarily because of budgetary and curriculum implications. In most cases, departments are not willing or able to modify their existing undergraduate control courses or to relinquish control over them to a centralized course. Laboratory facilities are likewise not easily shared among departments because of concerns regarding who will pay for equipment purchases and maintenance, technical support, and other considerations.

Many universities outside of the U.S. have separate departments of Automatic Control which provides service courses and laboratory instruction to the various departments. However, with a few exceptions, U.S. universities have not adopted this structure but continue to teach courses in control systems within the traditional departments of Electrical Engineering, Mechanical Engineering, Aerospace Engineering, etc.

## 2 Our Solution

To address these problems we have instituted a new laboratory structure in our College of Engineering, which we believe can serve as a national model for other universities. With strong support from the College of Engineering we have established the **College of Engineering Control Systems Laboratory**, a centrally located, interdisciplinary laboratory designed to service all of the basic instruction in control systems for all departments in the College of Engineering. This laboratory, which we will henceforth refer to as the **Core Laboratory**, has been operational since Fall, 1994, with eighteen (18) lab benches containing state–of–the–art equipment for instruction in feedback control systems. We have hired a full time Laboratory Manager, who has industrial experience and a Masters Degree with a specialization in Control Systems. Currently more than 550 students enroll each year in courses that utilize the Core Laboratory.

Funding for the Laboratory comes from a tuition surcharge paid by all students in the College of Engineering. This tuition surcharge was instituted specifically for the purpose of improving undergraduate laboratory facilities. In addition to supporting the Control Systems Laboratory these funds support the College Materials Testing Laboratory and a number of College Workstation Laboratories. The Core Laboratory was established by a committee made up of controls faculty from the various Departments in the College of Engineering. Initial startup costs for equipment, room remodeling, workbench construction and furniture was on the order of $500,000 and the yearly budget for the Laboratory is $125,000, which pays the salary and benefits of the Lab Manager in addition to the cost of routine maintenance and upgrades, new equipment purchases, and the construction of experimental apparatus. The College Controls Laboratory Committee that established the Lab now oversees the operation and continued development of the Lab, supervises and evaluates the performance of the Lab Manager, and coordinates the acquisition and development of the satellite labs.

The Core Laboratory concept is a good solution to the first of the above problems, namely, avoiding duplication of resources. Because the labs are a common resource to all departments, they can be funded at the College level and can be administered by committees chosen from the various engineering departments. The individual departments retain control over their specific courses and retain responsibility for providing lab TA's for these courses, while simply reserving laboratory time. It is the responsibility of the full–time lab manager to supervise the lab TA's and schedule lab sections of the various courses. This structure has been in place for more than a year and has worked very successfully.

In order to address the second problem above, which is to provide integration of systems concepts and laboratory experience to the students in the diverse curricula of the separate departments we are developing an integrated network of collegewide laboratories around the Core Laboratory to support more advanced undergraduate and graduate education in Control Systems Technology. Our development plan is based on the structure shown in Figure 1. The Core Laboratory, which

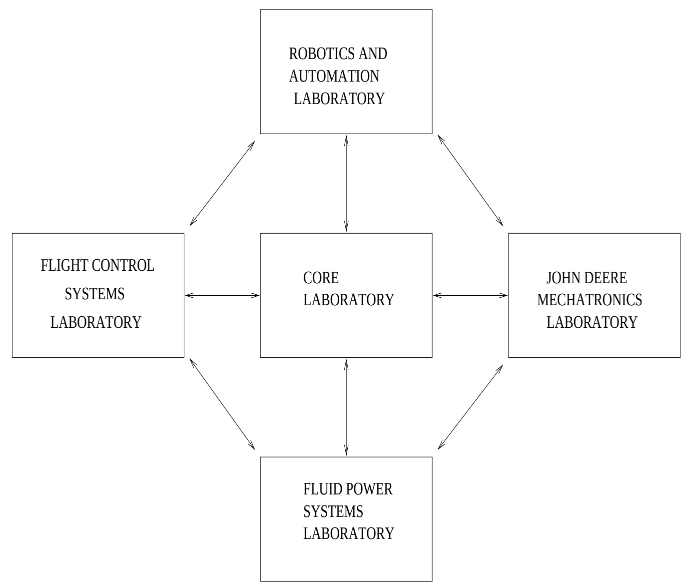


**Figure 1:** Our Laboratory Concept

is used in the introductory courses in feedback control systems, is surrounded by a number of **Satellite Laboratories** that service related courses and that rely on the common curriculum experience gained in the Core Lab. The same committee that administers the Core Lab also administers the network of satellite labs. Currently we have four satellite laboratories in various stages of development, the Robotics and Automation Laboratory, the John Deere Mechatronics Laboratory, the Fluid Power Laboratory, and the Flight Control Systems Laboratory.

## 3 Description of the Laboratories

In this section we describe in more detail our laboratory network. Because of space limitations we will focus primarily on the Core Laboratory and provide only brief descriptions of the satellite labs.

### 3.1 The Core Laboratory

The Core Laboratory (The College Control Systems Laboratory) became operational in the Fall semester of 1994. This Collegewide facility has many advantages over the individual department laboratories that it replaced. The main advantage is the pooling of resources, both equipment resources and intellectual resources. Perhaps the single most important advantage from a logistics standpoint is that, by pooling resources among several departments, it became feasible to hire a full time academic professional to manage the day–to–day activities of the laboratory. The laboratory manager frees faculty from maintenance and development chores and allows them to concentrate on the pedagogical aspects of the laboratory.

In a typical semester, the control lab is seen by almost three hundred students in five different courses within the College of Engineering. Currently, the facilities are used by the Department of Electrical and Computer Engineering; General Engineering; Aeronautical and Astronautical Engineering; and Mechanical Engineering. With such a large operation, substantial funds were required to get the lab started, and significant funds are required for maintenance, administration, and support. When the lab was created in the Summer and Fall of 1994, one half million dollars was used in total for the facilities. We have a recurring budget of $ 125,000/yr for maintenance and upgrades, as well as a budget for support personnel.

**3.1.1 Equipment and Experiments:** The lab is currently located within the Department of Electrical and Computer Engineering (ECE) within 3 lab rooms with 6 benches in each room. The lab benches were made with an optical table top for positioning equipment, and were constructed locally by the ECE machine shop. A photograph of a typical bench is shown in Figure2, each of which contains the following equipment:

**Figure 2:** Core Lab Workbench

- A PC-486DX2/66 workstation, each of which contains an Analog Devices RTI 815 data acquisition board, a National Instrument GPIB interface board, and a Dynamic Research Corporation Optical Encoder interface board.
- A Comdyna GP-6 Analog Computer.
- An HP 6632A Programmable Power Supply.
- An HP 54600B Oscilloscope.
- An HP 33120A Function Generator.
- An HP 34401A Multimeter.
- An Advanced Motion Control PWM Servo Amplifier
- An in house built Motor Assembly with Tachometer (Velocity) and Potentiometer (Position) feedback.

Software packages for networking, symbolic and numerical computation, simulation, and real–time control, such as Matlab, Mathematica, X-Windows, C, HPVee, Netscape, etc. are available, and each of the computer workstations is connected to the campus backbone computer network. In addition, six HP 35670A Dynamic Signal Analyzers are shared among the lab rooms four of which were acquired through a $132,522 donation to the Control Systems Laboratory by Hewlett–Packard.

With additional funds we purchased some extra equipment and a demonstration bench was constructed to bring the lab into the classroom. In addition to this, we also set up several new experiments:

12 Torsional spring modules were constructed by the ECE machine shop to mount to the DC motor units (see Figure 4). This creates a flexible control structure with interesting characteristics from the point of view of control.

6 *Pendubots* [2] were constructed, again by the machine shop (cf. Figure 3).

A "Noise Cancellation Plant" was purchased from Digisonix, Inc., primarily to demonstrate adaptive noise cancellation techniques for our adaptive control course.

A "Vibration Table" was purchased to demonstrate vibration cancellation using the internal model principle, or adaptive techniques.

The Pendubot is an electro-mechanical system consisting of two rigid links interconnected by revolute joints. The first joint is actuated by a DC-motor and the second joint is unactuated. Thus the second link may be thought of as a simple pendulum whose motion can be controlled by actuation of the first link. The Pendubot is similar in spirit to the classical inverted pendulum on a cart. However, because of the nonlinear dynamic coupling between the two links, the Pendubot possesses some unique features and challenges for control research and education not found in other devices. Using the Pendubot one can investigate system identification, linear control, nonlinear control, optimal control, learning control, robust and adaptive control, fuzzy logic control, intelligent control, hybrid and switching control, gain scheduling, and other control paradigms. One can program the Pendubot for swingup control,

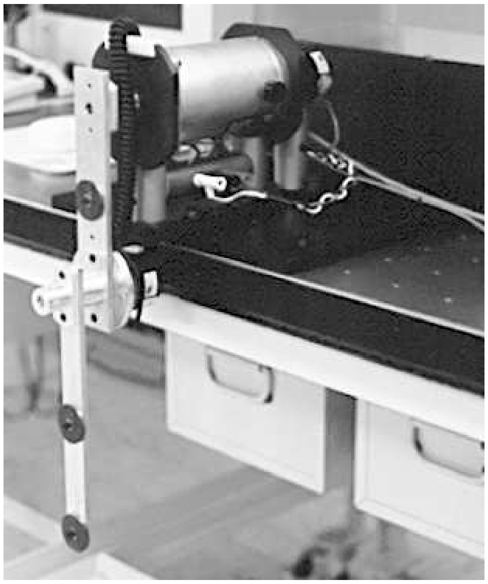

**Figure 3:** The Pendubot

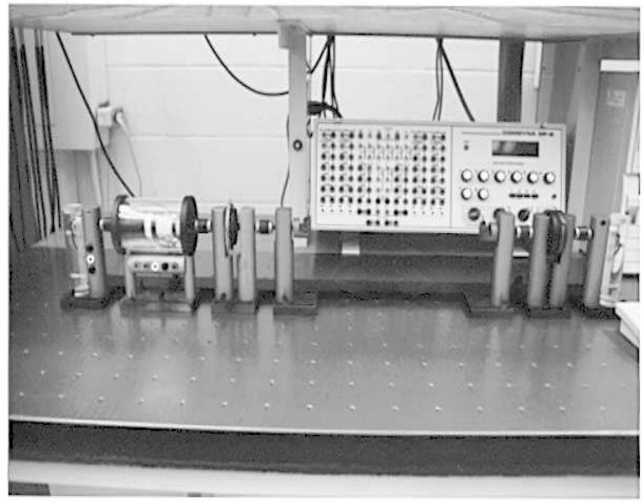

**Figure 4:** The Modular Torsional Plant with DC Motor

balancing, regulation and tracking, identification, gain scheduling, disturbance rejection, and friction compensation to name just a few of the applications.

**3.1.2 Usage of the Core laboratory in Courses:** All of our introductory feedback control systems courses in the departments of Electrical and Computer Engineering, Mechanical and Industrial Engineering, and General Engineering now utilize this laboratory for instruction in the basic concepts of control systems with emphasis on frequency and time domain modeling, state variable representations, and laboratory techniques.

After some initial introductory simulation studies using both an analog and a digital computer, the students look at identification and control of a DC motor. Additional experiments involve control of a torsional plant (see Figure 4) (mass-spring-damper), inverted pendulum, etc. In some courses, students complete a final project which varies from year to year.

### 3.2 Robotics and Automation Laboratory

The College of Engineering Robotics and Automation Laboratory was founded in 1987 as the General Engineering Robotics and Automation Laboratory. Original funding for the laboratory was provided by General Motors Corporation as part of the University of Illinois Manufacturing Engineering Program, by The University of Illinois, General Electric Company and by Zenith Corporation. During 1992–94 the laboratory was upgraded as a result of the NSF ILI grant USE-9251154, merged with the Electrical and Computer Engineering Robotics Laboratory, and subsequently became the College of Engineering Robotics and Automation Laboratory. The laboratory currently contains eight SUN workstations, 10 PC's, 6 Rhino robots, 2 PUMA robots, 2 Direct Drive robots with DSP–controllers, special purpose robotic devices, such as the Acrobot and the Pendubot, and various other devices such as conveyors, turntables, force sensors, and vision systems. Available software for robotics and controls includes, CimStation, Mathematica, Robotica, Matlab, Simnon, and other packages. The laboratory currently services all of our robotics courses, our manufacturing engineering courses, as well as graduate student research projects. A more detailed description of this laboratory is found in [3].

### 3.3 John Deere Mechatronics Laboratory

The John Deere Mechatronics Laboratory was made possible by a $125,000 grant from John Deere to support courses in real-time control and mechatronics. Project oriented courses in the design of electromechanical systems incorporating embedded microprocessors are being developed to teach concepts in real time programming, nonlinear, adaptive, and intelligent control. When fully operational, this laboratory will contain six workbenches identical to those in the Core Laboratory, together with an extensive collection of sensors, actuators, boards, design software, etc. to enable the design and realization of projects in mechatronics, such as design, construction, and control of a mobile robot, design of smart structures, vibration and noise cancellation, etc. The Mechatronics Laboratory also contains an active noise cancellation system and an active vibration control system, both produced by Digisonix, Inc.

### 3.4 The Fluid Power Systems Laboratory

The development of the Fluid Power Systems Laboratory is made possible by grants from several industrial partners including Parker Hannifin Inc. and Caterpillar

Inc. Additionally, the lab is supported by the National Science Foundation through Grant DUE-9650461. The focus of the lab is to reintroduce a common source of system actuation, Fluid Power, to undergraduate education in Dynamic Systems and Controls. Electrically controlled hydraulic and pneumatic systems will both be developed as part of the combined Fluid Power focus. The lab will support basic courses in System Dynamics as well as advanced control courses involving classical and modern controls, digital systems, intelligent systems, nonlinear systems and other topics. The laboratory will consist of 6 individually powered hydraulic test benches that will be interfaced to PC-based microprocessors. Each bench will have (i) a Hydraulic Power Supply, (ii) Electric solenoid driven valves, (iii) Hydraulic cylinder w/LVDT, (iv) Hydraulic Motor w/Rotary Encoder, and (v) Pressure/Flow sensors for Data Acquisition (DAQ). Rack-based DAQ systems will provide modular interfacing between the PC-based software and the system sensors. The Fluid Power Lab will support different types of data acquisition and control software including Matlab and LabView. In addition to the hydraulic experiments, there will also be 6 pneumatic control benches. Each bench will have (i) Modular pneumatic positioning experiments, (ii) Pressurized building air, (iii) Electronically driven valves and (iv) Sensors for DAQ. The DAQ setup will be the same one as the hydraulic benches. The modular experiments will consist of rotational and translational components that can be integrated to provide multi-degree of freedom motion control experiments. For the laboratory exercises, students will develop fluid models based on first principles such as control volumes, compressibility, continuity equations and orifice flow conditions. Electromechanical models will also be developed for the electrical and mechanical components. Model verification will be performed using System Identification techniques. Finally, controllers will be developed and implemented; first in simulation and then experimentally. Since many engineering systems contain some aspect of Fluid Power, this laboratory will provide valuable hands-on experience for students that will bridge the gap between classroom theory and actual industrial problems.

### 3.5 Flight Control Systems Laboratory

The Department of Aeronautical and Astronautical Engineering (AAE) has recently installed a reconfigurable flight simulator constructed by FRASCA International, Inc. The unit uses an integrated computer system which allows for six-degrees-of-freedom dynamics, simulate performance of propeller and jet engines, generate aircraft sounds, interact with student's control inputs and display information on the instructor operating station. This installation has the capabilities to be used for undergradute courses in control design equally well with great educational benefits. In particular, the unit includes a special computer-to-computer interface which allows the simulator to output data to a standard personal computer and to input data from the same PC. This capability can be utilized in order to incorporate feedback control laws (autopilot control system software) that interact with the simulator. As a consequence, several experiments can be developed which consist of designing autopilots and testing their performance through the simulator. The expected benefits of feedback operation can be magnified by considering models that are open-loop unstable and hence the handling of the aircraft is extremely hard if not impossible without feedback control. The simulator will provide a "virtual aircraft" to experiment with. The concepts of stability, maneuverability, responsiveness, etc. will be experienced first-hand by the students. It is expected that such experiments will play a vital role in making the students understand and further appreciate the role of feedback control in aircraft applications.

## 4 Summary and Conclusions

Our initial experiences in the development of a Collegewide network of laboratories have been uniformly positive. It may be useful to list some factors that have contributed to the success of our venture. These include:

A source of recurring funds. An undertaking such as we describe is only possible with the support of the College to provide recurring funds. Many educators have had the experience of developing laboratories with lump sum grants or donations only to see them become obsolete as technology evolves. In addition, the recurring budget has allowed us to hire a full time manager to oversee the day to day operation of the Lab. Without such a manager, instructional laboratories must be maintained by students, who tend to leave just as they become most useful, and by faculty, whose schedules do not permit them to engage in laboratory maintenance.

A willingness among faculty to share resources and ideas. The members of the College Controls Laboratory Committee, mainly the authors of the present article, have worked closely together to coordinate and to share laboratory experiments, developing new courses, visit industrial sponsors, prepare proposals for additional equipment, etc.

A willingness among department heads to provide reduced teaching loads to faculty members developing new laboratories or laboratory experiments.

With the development of our laboratory network to support basic instruction in control systems, comes additional opportunities once the laboratories are in place. Specifically we are turning our attention to developing exercises, demonstrations, and experiments to utilize the laboratories for activities beyond the basic courses. For example, we are

1. developing laboratory demonstration modules in each of the five laboratories for use in our required freshman course, Engineering 100. These modules will introduce to freshmen the fundamental concepts of feedback in dynamical systems, the systems approach to design, and the importance of new and emerging fields, such as mechatronics and virtual reality.

2. coordinating the laboratory instruction in the junior/senior level controls courses in the various departments. To this end, a repertoire of controls and controls related experiments are being developed in the five laboratories, which will be published together in a single catalog, and made available to any department wishing to use them. In this way, individual departments can retain control over their existing courses, while relying on the facilities available in the collegewide laboratories for their laboratory experiments. This catalog of experiments will be accessible over the internet, so that, experiments developed by one faculty member, are immediately available collegewide.

3. expanding the instruction in systems, control, and mechatronics to other departments in the College of Engineering beyond those represented by the present authors. For example, the use of "smart" sensors and actuators to help buildings withstand earthquakes are of interest to the Civil Engineering Department, while the use of mechatronic principles in the development of "smart materials" is of interest to the Materials Science Department. Our catalog of laboratory experiments and demonstration modules will encourage other departments to utilize our facilities and ultimately to become involved in laboratory development.

4. developing virtual experiments which can be accessed on the internet using the next generation of "Java enhanced" web browsers. These virtual experiments will allow the utilization of our on–campus laboratory facilities to off–campus students, students at other universities and even high schools that do not have access to the type of equipment available to us, and to engineers in industry interested in continuing engineering education.

5. working with industrial sponsors to incorporate real–world industrial projects into the laboratories as part of the senior design project courses in the various departments. We have already achieved some notable successes in this regard.

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