A Laboratory Course on Fuzzy Control

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***Abstract*—In this paper we describe a new control laboratory course at The Ohio State University. Students execute a series of laboratory exercises, for a variety of processes, implementing fuzzy control, adaptive fuzzy control, and other intelligent control techniques, with a particular focus on fuzzy control. Fully instrumented independent testbeds in the laboratory emphasize several sensing and actuation technologies. Both senior undergraduates and graduate students take the course and several have used the experience, coupled with research that they have conducted with our industrial sponsors, to obtain positions in industry working on intelligent control.**

***Index Terms*—Education, fuzzy control, intelligent control, laboratory.**

I. INTRODUCTION

KEY concepts and techniques in the area of intelligent systems and control were discovered and developed over the past few decades [1]. While some of these methods have significant benefits to offer, engineers are often reluctant to utilize new intelligent control techniques for several reasons: 1) there has been a lack of rigorous engineering analysis to verify, for example, stability properties and performance characteristics; 2) there is not an established track record for the reliability and robustness of such techniques; 3) there has not been enough comparative analysis to determine their advantages/disadvantages relative to conventional methods; and 4) the approaches are not widely understood by practicing engineers. The relative lack of attention given to the potentials of intelligent control, especially in American universities and industry, is cause for some concern, indicating a definite need for applications-directed research and education in these areas.

Curricula for control engineering programs has undergone substantial change in the past 30 years as modern techniques for analysis and design find their way into our college courses. It is quite natural, then, that newer technologies such as intelligent control should be introduced into university curricula. Along with the continuously evolving curricula, there remains a constant in control engineering education: the recognized need for laboratory experience in the curricula. More and more examples of high-quality control laboratories are appearing in universities around the world. Moreover, more and more educators recognize the importance of a complete educational experience involving theory and practice.

With these thoughts in mind, it has been the goal of the Ohio State control group to bring the newest technologies into the curricula, through both lecture and laboratory courses. In 1993, the authors were awarded a National Science Foundation Combined Research-Curriculum Development grant for incorporating new techniques in intelligent control into the curriculum. The incorporation of existing research results in intelligent systems and control into the curriculum was accomplished via a lecture course introducing intelligent control theory, a follow-up lecture-laboratory course, and a parallel senior design project activity. The focus of this paper is on the lecture-laboratory course; however, we do describe several other details of our curriculum in control.

There exist numerous control laboratories around the world for the instruction of classical, modern, and intelligent control techniques; the interested reader is referred to [2] for a thorough exposition and guide to several citations. The novelty of the laboratory course reported herein is in its focus on fuzzy control algorithm implementation. In particular, the laboratory demonstrates several key attributes of fuzzy control, including control design with limited conventional modeling exercises, heuristic construction of nonlinear controllers, comparative analysis with conventional controllers, needs/advantages of adaptation for fuzzy controllers, and the role of rule-based supervisory mechanisms via lectures on complex industrial applications. Moreover, we go beyond the treatment of only fuzzy control by providing the opportunity to implement neural networks and genetic algorithms for estimation and control (i.e., we include other methods in intelligent control via special projects for the students based on their interest).

II. CONTROL CURRICULUM AT THE OHIO STATE UNIVERSITY

A. Overview

To set the stage for description of the Intelligent Control Laboratory course, we briefly describe the Department of Electrical Engineering's control systems curriculum at Ohio State. There is an undergraduate course on control and its corresponding laboratory. At the time of this writing, 16 graded courses are offered at the beginning graduate (also available as senior electives) and advanced graduate levels (eight of each). Six of the advanced-graduate level courses alternate on an every-other-year basis, meaning that 13 courses run every year. The topics covered in the lecture-only courses available for graduate credit are: Filtering and Estimation in Control, Linear Systems, Feedback Control II, Topics in Control Applications (Powertrain Control, or Autonomy in Vehicles), Nonlinear Systems, Digital Control, Advanced Linear Systems, Stochastic Control, Adaptive Control, Nonlinear

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Control II, Optimal Control, Large-Scale Systems, Robust Control, and Intelligent Control.

The Control Group at Ohio State is recognized for its instructional control laboratory courses, and has more than ten years experience in their development (see, for example, [3]–[5]). Currently, in addition to the undergraduate core Control Systems Laboratory course, the curriculum offers two lecture-laboratory courses at the senior/beginning-graduate level. The first is the Digital Control Laboratory course, a three-credit hour lab/lecture course which emphasizes several important aspects of digital control: instrumentation issues (sensors and actuators), microprocessors, operating systems, and high-level control languages. The second of these laboratory courses is the Intelligent Control Laboratory.

B. Intelligent Control Sequence

The lecture-only Intelligent Control course mentioned above was introduced as part of a sequence of courses aimed at bringing current research on intelligent systems and control into the curriculum. The second course of this sequence is the subject of this paper, and is discussed in the sequel.

The two-course sequence (which ran for the first time in the 1994–1995 academic year) is offered at the graduate level, and is available as a senior elective sequence for motivated undergraduates (where undergraduates complete only a portion of the laboratory and course). The topical outline for the three-credit hour lecture-only course is:

- Fuzzy control: direct, adaptive, and supervisory;
- Neural networks: multilayer perceptron and radial basis function neural network; neural estimation and control;
- Stability analysis adaptive fuzzy/neural control systems;
- Fuzzy/neural systems for identification and estimation;
- Genetic algorithms for computer-aided control design, adaptive control, and estimation.

With regard to the treatment of fuzzy control in both courses, our intent has not been to give an in-depth treatise on the theory of fuzzy sets. We have found that electrical engineering undergraduates (through independent research projects) have little difficulty in “coming up to speed” in the area in a relatively short amount of time. Thus, sometimes as part of this independent study undergraduates take the first portion of the above course (the direct fuzzy control material), and then implement fuzzy controllers in the lab to complete their study.

The graduate students are exposed to the more advanced topics listed above, and at a higher level of sophistication. Several projects in simulation, design, and stability analysis are given. Then the graduate students are required to complete the entire lecture-laboratory course described in the next section. Finally, we note that other courses in artificial intelligence, neural networks, and expert systems for monitoring and control are available at OSU.

III. LECTURE-LABORATORY COURSE

A. Course Overview

The Intelligent Control Laboratory course capitalizes on the long-standing strength of the Ohio State control group in applied control research. Moreover, it builds further on an existing educational laboratory facility resulting from a NSF award under the Instrumentation and Laboratory Improvement Program (see [5]) for our undergraduate controls laboratory. The course serves as a complement to the Digital Control Laboratory course, although neither requires knowledge from the other. Both courses now run off the same equipment (computers, data-acquisition hardware, and instrumentation). Whereas the existing Digital Control Laboratory course emphasizes machine-level programming and aspects of hardware, the Intelligent Control Laboratory course focuses strictly on aspects of designing and applying intelligent control and conventional control algorithms to a variety of real processes, with little attention given to details of digital implementation (principles of A/D and D/A conversion, word length restrictions, and so on). That is, due to the nature of the experimental testbeds targeted for this project, the majority of the crucial control software is already in place, and students are only required to write control subroutines in C and C++. Thus, many students take both laboratory courses because of their differing emphasis.

The course consists of two lectures per week, with several hours per week in the laboratory. Important features are:

- active participation in current research directions through hands-on experimentation with testbeds for comparison of conventional and intelligent control techniques;
- introduction to special purpose hardware (e.g., OMRON Electronics fuzzy processor) and software (such as OMRON software, and fuzzy control toolboxes for Matlab) for intelligent control analysis and design;
- report requirements which will draw from current research, relevant applications, and experimental experience in presentation of results.

A portion of the lectures focus exclusively on the laboratory experiments (details of coding, research-related issues, modeling, and control objectives), and a portion focus on the necessary intelligent control design issues. As requirements for the course, students are expected to conduct projects (analysis, design, and application) on several of the testbeds over the course of the quarter. Required reports not only summarize the techniques, procedures and results of the individual experiments, but also explore additional nuances as directed by the accompanying exercises in the lab notes.

B. Syllabus

Each laboratory section (two sections were conducted in Spring 1995) is limited to eight students, and students work in pairs. The basic course structure for the ten-week quarter is as follows.

Week 1: Laboratory Software: Exercises for this laboratory require the student to use Microsoft Windows, Matlab for Windows, C programming skills, and Borland C++, all of which are used in the remainder of the course. Basic procedures include comparing designs of digital filters in C and Matlab.

Week 2: Laboratory Hardware: Students are introduced to the capabilities of the data acquisition instrumentation. Procedures include writing routines to access signals from a waveform generator, implementing digital filters written in C which interface with real signals, and making comparisons to Matlab simulations.

Week 3: Matlab Toolboxes: Students are introduced to special-purpose, commercially available tutorial fuzzy control software for Matlab. Procedures include use of available functions and demos, design and simulation of a dc motor fuzzy controller, and various tuning exercises on the developed controllers.

Week 4: DC Motor Control: Students gain their first experience of actual implementation. Several dc motor setups with variable loads are instrumented, offering excellent "starter" experiments for students with limited control laboratory experience. Procedures require students to implement and tune fuzzy controllers (designed in Week 3) in C code.

Week 5: Direct Fuzzy Control: After the first four weeks of introduction, along with the accompanying lectures described below, students spend the remaining six weeks of the term implementing controllers on laboratory testbeds (described in the next section). Students implement a "direct" fuzzy controller on one of the following: the rotational inverted pendulum, ball-beam system, process control plant, inverted pendulum on an inverted wedge (recently developed experiment), or flexible arm. Although each testbed emphasizes entirely different actuation and sensing technologies, procedures for each are basically the same: design and implement a fuzzy controller (varying from two-input to four-input controllers) and compare to conventional control designs.

Week 6: Direct Fuzzy Control: Students repeat procedures carried out in Week 5, but on a different testbed.

Weeks 7–8: Adaptive Fuzzy Control: Students design and implement an adaptive fuzzy control algorithm on one of the four laboratory testbeds. Each testbed affords interesting problems requiring controllers that can adapt to plant parameter variations so that higher performance control can be achieved. Procedures also include comparison to direct (fixed) fuzzy controller designs.

Weeks 9–10: Project in Intelligent Control: Students carry out projects which go beyond the first eight weeks of the course in terms of methods applied and control objectives. A variety of intelligent control (and also estimation or system identification) techniques are acceptable, including fuzzy, expert, neural, or genetic algorithms. Application is on one of the laboratory testbeds, on the programmable logic controllers (complete state-of-the-art PLC units and development systems from Modicon are available), on the OMRON fuzzy processor, or, in special cases, even on a process outside the laboratory.

C. Lectures

There are ten lectures given in the laboratory in parallel with the above labs. These are:

1) laboratory orientation, Fuzzy controller C code;
2) fuzzy systems toolbox demonstration;
3) applications of fuzzy control: surge tank, ball-beam (video);
4) applications of fuzzy control: rotational inverted pendulum (video);
5) applications of adaptive fuzzy control: two-link flexible robot;
6) applications of adaptive fuzzy control: reconfigurable control;
7) applications of supervisory fuzzy control: PID autotuning;
8) applications of supervisory fuzzy control: two-link flexible robot;
9) fuzzy versus conventional control: advantages and disadvantages;
10) intelligent versus conventional control: advantages and disadvantages.

These are weekly lectures of one hour or more in length.

IV. LABORATORY TESTBEDS

All testbeds are controlled by 486-based PC's (operating at 50–66 MHz), introducing a uniformity which is vital in such an instructional laboratory. Additional processor hardware (within the PC's on selected stations) include the OMRON FB-30AT Inference Board, FP-3000 Digital Fuzzy Processor, and FS-10AT Inference Software. Data acquisition for each station is accomplished with the Keithley Instruments DAS-20 card. Each PC has an ethernet connection, 16-MB ram, and the Windows 3.1 operating system.

It is important to note that each testbed emphasizes different sensing technologies, including optical encoders, potentiometers, thermal measuring devices, and accelerometers. Actuation is accomplished with dc and ac motors, including servo-controlled pumps and high-torque motors.

A. Rotational Inverted Pendulum

A classic control problem is the inverted pendulum. Most conventional setups consist of a pendulum hinged to a moving cart (driven by a belt or chain) on a linear rail. In this experiment another idea (see [6]) is used in which the pendulum is fixed by bearings to a rotating arm.

This test bed, the result of [7], consists of three primary components: the plant, digital, and analog interfaces, and the digital controller. The overall system is shown in Fig. 1. The plant is composed of a pendulum and a rotating base made of aluminum rods, two optical encoders as the angular position sensors with effective resolutions of 0.2 degrees for the pendulum and 0.1 degrees for the base, and a large, high-torque permanent-magnet dc motor (with rated stall torque of 5.15 N-m). As the base rotates the pendulum is free to rotate (high-precision bearings are utilized) through its angle made with the vertical.

Control objectives for this testbed are twofold: swing-up of the pendulum to the vertical position, and then balancing the pendulum. Adaptive techniques are required when a weight is added to the end of the pendulum, and when additional dynamics are added by attaching a half-filled bottle of water to the end, which introduces a "sloshing liquid" effect.

B. Ball-Beam System

Another classic control problem is to balance a ball in a groove by tilting a platform on which the ball balances

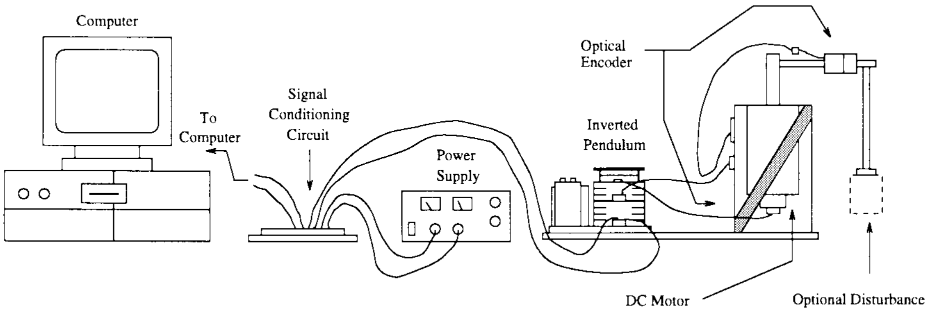

Fig. 1. Rotational inverted pendulum.

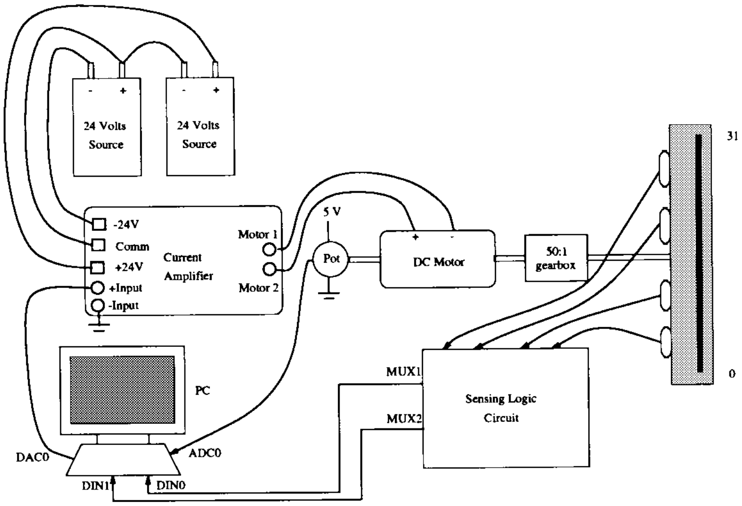

Fig. 2. Ball-beam testbed.

(see Fig. 2). Unlike commercially available setups which use continuous resistive sensing of the ball position, this apparatus was built in-house as an undergraduate research project [8]. The testbed is also distinguishable from other devices like it in that it uses discrete sensing of the ball position via a row of 32 phototransistors. Two light sources are used to illuminate the beam from above, so that the ball position is sensed according to its shadow cast on the phototransistors. The angular position of the beam is sensed using a potentiometer, while a dc motor provides actuation of the beam via a 50 : 1 gear ratio.

The objective of control experiments is to move the ball from one position (at rest) to another position along the beam. Adaptation is required when different-sized balls are used on the platform, and also due to inherent nonlinearities (including deadband and backlash introduced by the dc motor and gearbox configuration), discrete sensing, and an uneven rolling surface.

C. Flexible-Link Arm

The single and multiple-link flexible arms serve as excellent testbeds for nonlinear control (in large-angle movements) and vibration suppression control (for endpoint positioning). The control group at Ohio State has done work with one, two, and three-link flexible robot arms for more than 13 years, and much of that expertise has been brought into this laboratory course; see, for example, [9]–[11].

The flexible-link robot testbed consists of a single lightweight flexible arm counterbalanced with a rigid appendage (see Fig. 3). The arm is actuated by a dc motor at the base, accompanied by its own controller/servo amplifier. A high-resolution optical encoder gives angular measurement of the motor shaft, and signal conditioning similar to the pendulum testbed is used prior to sampling. An accelerometer mounted at the endpoint of the flexible arm is used to measure linear acceleration at the endpoint. This device is produced by Kistler, and has the Kistler Piezotron Coupler as interface; that output is passed through an analog low-pass filter prior to sampling. A small incandescent bulb is mounted on the endpoint, which is used in conjunction with a linear array line-scan camera to record movement of the endpoint. The camera system is interfaced with a separate PC, and is used solely for displaying endpoint position, not for feedback control.

The objective of this testbed is to investigate the ability of intelligent control techniques to suppress unwanted vibrations at the endpoint as the arm undergoes large and rapid slews. Thus, a typical control experiment is to begin with the arm initially at rest, then to slew through an angle of 90°; feedback variables include the angular position and velocity of the hub (motor shaft), and the endpoint acceleration. Controller adaptation is required when an extra weight (payload) is attached to the endpoint.

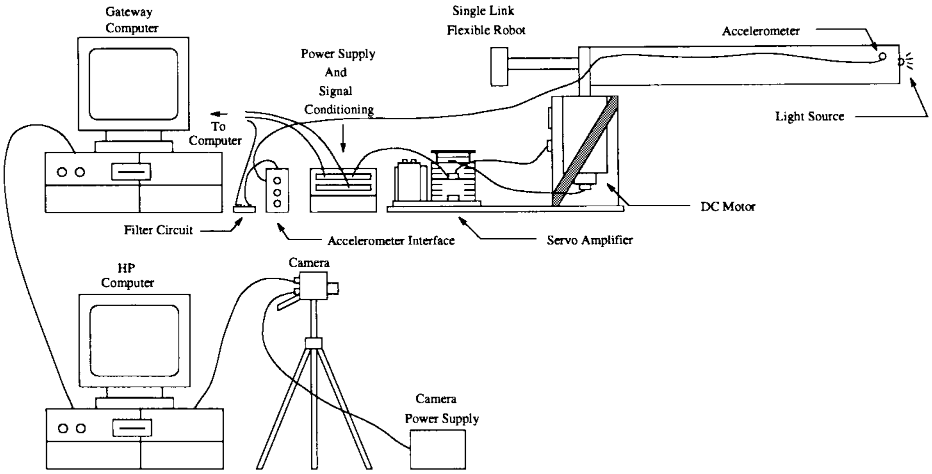

Fig. 3. Flexible-arm testbed.

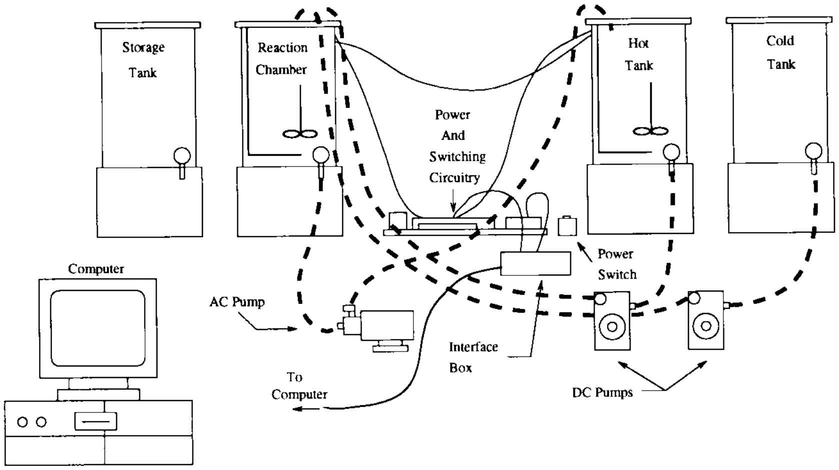

Fig. 4. Process control testbed.

D. Process Control Plant

An often used example for illustration of conventional and intelligent control is the chemical mixing process control plant. This testbed consists of four tanks, four liquid-level measuring devices, two temperature measuring devices, two mixers (stirrer fans), and two heaters (see Fig. 4). The liquid level in each tank is measured by a potentiometer attached to a styrofoam float. Temperature measurements are made via temperature transducers mounted in the "reaction" chamber (where hot and cold liquid is mixed) and in the hot tank, which each contain a heater and stirrer. An ac pump is used to remove liquid from the reaction chamber, while two dc pumps move liquid from the hot and cold tanks to the reaction tank. The ac pump, heaters, and stirrers may be turned on or off independently, making up five of the plant's inputs. The flow rate of the two dc pumps may be varied independently by changing their supply voltage (via a PWM scheme), comprising the remaining two plant inputs.

The objective of the experiment is to investigate the fundamentals of intelligent process control, with real-life implementation problems such as sensor noise, significant time delays, and the lack of a good mathematical model of the plant. The temperature and level sensors, with heaters and stirrer fans, are used in a variety of control objectives on the setup (e.g., temperature or liquid level regulation). Specific problems of the setup, making accurate control difficult, include accurate sensing of the liquid level (in the presence of turbulence due to the pumping action) and deadband nonlinearity in the dc pumps. We can also simulate a pump degradation failure (as if the filters in the pumps get dirty); compensation for this requires adaptation [12].

E. Development of New Experiments

We have an on-going effort to develop new experiments that may be used in the laboratory. Recently, we have completed the construction of an inverted pendulum on an inverted wedge. This experiment presents a significantly challenging nonlinear control experiment where we can study control of an inverted pendulum on an inclined plane (by fixing the inverted wedge position) or balancing of an inverted wedge (by removing the pendulum). In addition, one can try to solve the simultaneous wedge-pendulum balancing problem. We are also in the process of constructing a magnetically levitated ball that uses a photo-resistive strip as a ball position sensor. Such experiments are normally constructed by undergraduates as their senior design projects.

V. IMPACT OF THE COURSES

In this section we provide a brief discussion on the impact of the course on intelligent control and the intelligent control laboratory.

A. Student Reaction

The students generally responded very positively to the lecture and lecture-laboratory courses. There were over 40 students that completed the lecture course in Spring 1995 and 16 students who completed the laboratory (with four undergraduates). There were about 30 students in the lecture course in Spring 1997 and 12 in the laboratory. The students provided many positive comments on the student evaluations of instruction. For instance, they very much liked the fact that we kept them away from low-level implementation issues and felt that the course and laboratory were nicely in synch with each other. They liked the laboratory lectures and felt that they helped see how they could apply the methods to even more complex industrial applications. Several students made direct use of the intelligent control course and laboratory in their M.S. research and two journal papers were subsequently published on some projects done in these classes (students especially like this). There were a few complaints about problems with laboratory equipment, but such complaints were minimal as most of the equipment is new. Overall, the students felt that they had been provided a unique and valuable learning experience that they would be of benefit to them in their careers.

B. Textbook, Laboratory Manual

The authors have created a laboratory manual for the intelligent control laboratory that contains all the laboratory assignments and discusses all the necessary details on how to complete the laboratories. In addition, the authors have written a textbook on fuzzy control [13] that includes an instructor's manual (and indicates how to get the laboratory manual that we use). It is our hope that these publications will help to spread the curricular developments at OSU to other universities.

C. Impact on Industry/Government Laboratories/Universities

OSU has a long standing tradition of contracted industrial research in control systems. We have conducted research on intelligent control for or with several industries/government laboratories or have given short-courses or seminars in intelligent control for them (please see the acknowledgment section for a list). Our graduate students are especially well prepared for work with our industrial sponsors due to their exposure to the theory, application, and implementation of intelligent control methods. Moreover, the interactions with these companies has enhanced our research and educational programs (e.g., by providing thesis topics or examples for classroom discussion).

We hold a biannual OSU Control Workshop (which is a gathering at OSU of roughly 100 professors and graduate students from Midwest universities) where we provide a "laboratory open house." These laboratory tours help to facilitate the spread of our curricular advancements. Another way that we have spread ideas about the courses is through publications at international conferences. See, for example, [14] and [15].

VI. CONCLUDING REMARKS

In addressing the need for bringing intelligent control research into the curriculum, we have developed a sequence of courses accessible to advanced seniors and graduate students interested in theory and application of intelligent control. The sequence ran with great success for the first time in early 1995, with more than 40 students in the lecture course and 16 students in the laboratory course. It has run regularly since then. Students exiting the sequence are equipped with the ability to design controllers and estimation/identification techniques using fuzzy logic, genetic algorithms, and general rule-based systems. Students who also take the laboratory course have first-hand experience at implementing real-time intelligent control and estimation algorithms, and are well situated for placement in the job market. It has not been our intention to exhibit documentation and comparative anlaysis of control algorithms taught and implemented in the course; the cited references do a complete job of this.

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