The Development of a Shared Interdisciplinary Intelligent Mechatronics Laboratory

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ABSTRACT

This paper describes experience in developing an interdisciplinary mechatronics laboratory and success in using the lab to support academic instruction. It emphasizes the strategies and procedures that were important in creating an interdisciplinary laboratory in a traditional discipline-oriented academic institution. The strategies address objectives, acquisition and allocation of funding, and exploiting the existing infrastructure. Procedures such as the formation of a managing body and support for staff are also an important aspect of successful interdisciplinary laboratory development. The specific use of the lab is illustrated by two case studies, and its various benefits are discussed.

I. INTRODUCTION

Modern manufacturing, providing airplanes, cars, computers, and myriad other complex products, depends on the harmonious blending of many different technologies. The need for technology integration has been well recognized by designers, manufacturers, and educators and has received growing attention by many technical colleges and universities world-wide in recent years. However, many educational institutions find it difficult to fit mechatronics, "the synergistic combination of precision mechanical engineering, electronic control, and systems thinking in the design of products and manufacturing processes,"[1] within the traditional course structures of electrical, mechanical, industrial, computer, and other engineering departments. One common problem is the lack of infrastructure to support cooperative hands-on learning across traditional disciplinary boundaries.

Although courses addressing instrumentation, design, modeling, and control of mechanical and electrical systems are commonly found in individual academic units, few specific courses and laboratories have been designed to offer students an opportunity to integrate their learning experiences across their disciplinary boundaries. At Georgia Tech, many of these courses are technical electives within the Computer Science, Electrical and Computer Engineering, Mechanical Engineering, and Industrial and Systems Engineering programs. Although both simulation and hands-on experiences are essential to the effective learning of mechatronics, most courses often depend only on computer simulations and have no laboratory component. Some instructors manage to support limited instructional laboratory activities using facilities acquired through their related sponsored research effort. However, the suitability, accessibility, and maintainability of such labs are often less than desirable. As a result, the vast majority of students who pass through disciplinary halls lack hands-on and application-based mechatronics experience.

Over the years, employers have expressed strongly that our graduates should be better prepared to relate concepts learned in modeling and control courses to real modeling and control applications. Many educators have further pointed out that the lack of hands-on laboratory exercises limits the understanding of underlying basic concepts.[2,3] As a result, many employers find that valuable resources must be invested in intensive, on-the-job training to prepare college graduates for engineering employment.

Many factors contribute to this situation. Discipline-based budgeting practices simultaneously place pressure on the funding of instructional laboratories and create artificial barriers to collaborative funding of facilities that could be shared between disciplines. This problem has recently become more acute because of budget tightening in higher education and, if overlooked, will cause a weakening in the competitive edge for US industry in the global market place. A critical issue in solving the problem is acquiring funding and maximizing its leverage in the delivery of interdisciplinary modeling and control courses.

Traditionally, the individual laboratory for a technical elective is used only when a particular course is offered. Most technical electives are offered infrequently, often only once per year. In a quarter system, this means that the potential instructional laboratory utilization is only three months (25%) of the year. The actual usage is normally significantly lower because the utilization is significantly lower than 100% in a quarter when the course is offered. During the idle period, there are many other courses offered on campus that could potentially benefit from these laboratory resources, yet either have no access to the laboratory at all or are limited to computer simulation. For this reason, we present here a case study of a "shared" laboratory which we have implemented at Georgia Tech, jointly funded by the Computer-Integrated Manufacturing Systems (CIMS) Program[5] and the AT&T Foundation. Apart from improved cost-effectiveness resulting from the sharing of the laboratory's resources among participating units, both the students and the instructors have benefited from the exposure and interaction with participants from other disciplines.

This seemingly convincing and simple concept faces many challenges in any research institution where disciplinary organization and individual focus have dominated for years. We have identified six key elements for successfully meeting these challenges:

- funding,
- support,
- coverage,
- format,
- operation, and
- promotion.

Each of these issues is addressed below. After three years of effort, a sustainable shared Intelligent Mechatronics Laboratory successfully supports over 200 students in over 10 courses across 3 academic units each year. This article describes our effort and strategies in the development of the Intelligent Mechatronics Laboratory.

Mechatronics, as defined by Comerfeld in Reference 1, is an ideal theme for a multidisciplinary laboratory facility. Students clearly benefit from hands-on experience with the physical implementation of mechatronics. Mechatronics is appropriate for students from several traditional disciplines. Finally, a significant number of graduates will work in the field of mechatronics and must function in interdisciplinary teams.

Traditionally, the division between academic units at Georgia Tech has been rigorous, creating significant barriers to interdisciplinary education for both students and faculty. In the mid 1980s', a major effort led to the establishment of a master's level certificate program: Computer Integrated Manufacturing Systems (CIMS).[4] The participating units include: College of Computing (CoC), all Schools in the College of Engineering, and College of Management. The certificate program encourages students to pursue interdisciplinary studies involving computer science, engineering, manufacturing and management. This certificate program has produced 586 graduates as of September, 1996, and has enjoyed active support from industry.

We have been heavily involved in the CIMS program in administration, curriculum development, and teaching. We recognized that a significant weakness in the program was the lack of a truly interdisciplinary instructional laboratory. Through a strategic planning process, the development of such a laboratory was identified as a high priority initiative.

The first and most serious challenge in developing any new instructional laboratory is funding. While there are numerous potential funding sources, both internal and external, obtaining funds from any of them is quite challenging. Especially difficult is the acquisition of funds from internal sources to create a new (and therefore untested) instructional laboratory that will not be controlled by any one of the disciplinary units.

Recognizing this situation, our strategy was to create the laboratory using external sources and demonstrate that the concept of a shared instructional laboratory is feasible. With a "proof of concept" demonstration, the chances could be significantly improved for convincing the administration of the benefits of sharing and leverage from relatively small levels of long-term funding for lab operation from the institute's budget.

We first approached one of our CIMS member companies, AT&T. They were convinced of the value of the concept and provided $125,000 seed money from AT&T Foundation. We then formed a steering committee consisting of faculty members from CoC, Electrical Engineering (EE), Industrial and Systems Engineering (ISyE) and Mechanical Engineering (ME), an industry representative from AT&T, and a member of the Manufacturing Research Center staff. The committee chair rotates among the steering committee members on an annual basis. The first action by the steering committee was to draft a mission statement. Based on the mission statement, we defined the equipment acquisition policies and operational procedures. The steering committee also oversees the overall operation of the lab.

During the first three years, the success of the lab can be partially reflected from the rapid growth in the number of course sections utilizing the lab and faculty participation (Figure 1) and student participation (Figure 2).

The remainder of the paper is organized as follows:

- the mission of the laboratory;
- the location, facilities and operation of the laboratory; and
- two case studies of typical usage of the laboratory.

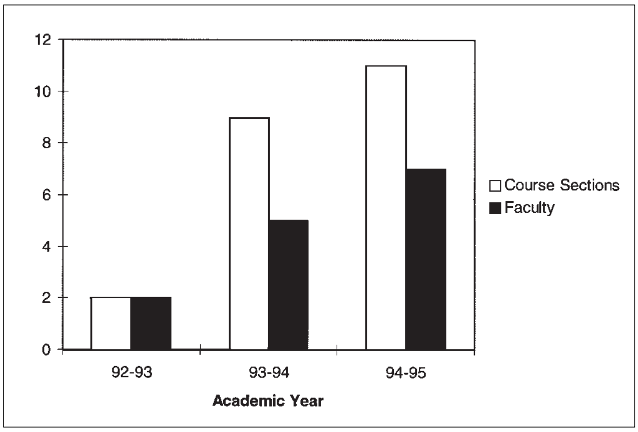

Figure 1. The number of course sections utilizing the lab and faculty participation.

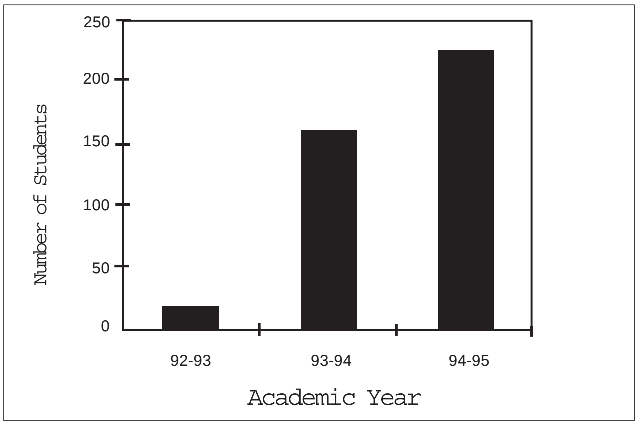

Figure 2. The number of students utilizing the lab.

II. Laboratory Mission

The laboratory was named the "Intelligent Mechatronics Laboratory (IML)." This title encompasses the targeted courses in sensing, control, modeling, and artificial intelligence and appeals to both faculty and students from many disciplines. After a lengthy discussion within the steering committee, we adopted the following mission statement:

"The mission of IML is to develop a laboratory that prepares students for the balanced integration of sensors, actuators, energy sources, controls, and information technology to achieve optimized functionality in the realization of industrial and consumer products. The IML supports learning that is directed toward both the product design and the design of the process necessary to produce it. In particular, the IML focuses on device, process, and product technologies. IML supports teaching engineers to integrate mechanical engineering, electronics, control engineering, robotics and automation and computer science into fundamental design processes."

This mission statement has been the guiding principle for the steering committee for resource allocation, lab operation, and other laboratory activities.

III. Laboratory Description

The IML is located in two adjacent rooms totaling 1,700 ft^2 in the Manufacturing Research Center (MARC). It supports instruction at both the undergraduate and graduate levels of mechatronics and automation. At the beginning of the project, the steering committee solicited brief proposals from faculty in all related academic units. The committee reviewed the proposals and decided which proposals to support based on the mission statement and projected overall impact. During the first year, several exercises on digital control, computer vision, and robotics were set up. In order to get more faculty and student involvement, we created a pamphlet describing the mission, facility and operation of the lab. The pamphlet was distributed to all related academic units. The pamphlet increased awareness of the IML and got a few more faculty members involved. After three years of acquisition, the lab has the following hardware and software facilities:

- TI TMS320C31-based dSpace Controller and software.
- seats of In-Touch supervisory control and data acquisition software.
- Rhino instructional robots and XY-table.
- Motorola 68332-based Mobile Robots.
- 386-based Vision-guided Mobile Robots.
- Legged robots.
- PCs
- Sun SPARC IPCs
- Computer Vision Systems
- Allen Bradley PLCs
- TMC-1000 3-axis CNC machining center

The computers associated with various devices are connected via a local area network, which provides support for backup, printing and file transfer. The network also allows off-line programming at computers not directly connected to the devices for certain exercises. The facilities have supported instructional experiments in the following courses:

- CS 3361 Introduction to Artificial Intelligence
- CS 4324 Intelligent Robotics and Computer Vision
- CS 6362 Applications of Artificial Intelligence
- ISyE 4256 Industrial Robotic Applications
- ISyE 6520 Computer Control in Manufacturing Systems
- ISyE 4897 Manufacturing Systems Honor Class
- ME 4055 Experimental Project Engineering (Control)
- ME 4449 Numerical Control of machine Tools
- ME 6437-8 Digital Control Systems I, II
- ME 8403A Machine Vision

Currently, there are 3-4 courses using the lab each quarter. The chair of the steering committee coordinates lab utilization through electronic mail. Before the quarter begins, the instructors of any courses intending to use the facility submit a brief plan to the chair. This plan includes the equipment to be used, format of usage and the weeks in which it is needed. If no conflict is apparent, the courses will be conducted as proposed. If there is a conflict, the chair works with the faculty to reschedule the labs. To date, we have had no schedule conflict that was not easily resolved.

Some instructors bring their students to the lab and give a brief introduction to the assignment and the use of equipment. Others provide detailed instructions to the students and let the students work independently at their own pace with occasional help from the lab assistants. To avoid unnecessary waiting, we post sign-up sheets for each lab setup. Individual student or project teams sign up for specific time slots in which they intend to work on their exercise.

We believe that one key to the success of the lab is its openness. The lab is staffed on weekdays from 9 AM to 6 PM by graduate student laboratory assistants. Their responsibilities include setting up experiments, providing lab instructions and helping student in exercises. As reported in Reference 5, the development of laboratory exercises offers great opportunity for graduate students. In two cases, lab assistants linked their thesis research on computer vision with laboratory exercise developments.

Some of the benefits of this lab are directly related to its "shared" or interdisciplinary nature. For example, a "pick and place" exercise was created in a CS course and then modified by an ISyE instructor to incorporate path planning concerns. The students in ISyE learn some CS concepts in the process that otherwise would not have been available. Another example is that a group of ISyE students worked on a palletizing assignment while a group of CS students worked on a collision avoidance exercise. The ISyE group incorporated the collision avoidance in their final project on a complex pick and place application.

While the benefits of a shared instructional lab have become obvious to the faculty and students, selling the concept upward through the administrative hierarchy remains a challenge. At present, the Georgia Tech administration, recognizing the leverage obtained, provides support for graduate student lab assistants. It is clear, however, that continued internal support will require a continuous selling effort.

IV. Case Studies

We now present two case studies to illustrate the operation of the lab. The first case typifies how the lab is used in courses. The second case shows that the lab can also be used to support other student activities, in this example supporting a robotics competition.

A. ME 6437-8 Digital Control Systems I, II

The following describes a course in digital control, taught in the Intelligent Mechatronics Laboratory at Georgia Tech. The intent of the course is to enable engineers to conceptualize and prototype mechatronic systems in which the function and performance are heavily determined by computer control. This course is taught in a lecture/lab format, with heavy emphasis on laboratory experience. The laboratory exercises involve the C language, DSP-based real-time simulation and control, identification and estimation, multi-processing real-time systems, and the use of digital vision system as a feedback element in control systems. Specifically, two creative multiprocessor control projects are described, where a non-conventional digital vision sensor is used as a feedback element. The non-conventional flexible integrated vision system (FIVS) has been developed at Georgia Tech, and has been designed to overcome some problems associated with the use of conventional vision systems for real-time control.[6-9]

Students come from a background in engineering, mostly mechanical, with some from aerospace and electrical. Typically, they are first year graduate students, having already taken a course in the fundamentals of digital control systems. Very few of the students have had any experience with MATLAB, Simulink, real-time software, or with the C language. This is a subject in which the learning takes place in the laboratory. The lecture portion of the course is intended to give students material that can be used in the lab. The lectures also are used to introduce a perspective on professional practice and typical applications of real-time software in the industrial world.

The laboratory practice has been broadly divided into two parts. The first part is to introduce basic concepts and techniques of design and implementation of digital control systems in a multi-processor environment. Emphasis is on providing students with hands-on experience in techniques such as timer interrupt-service-routine, bus and shared-memory, synchronization, and adaptive parameter update in performing multiprocessing real-time techniques. Several short tutorials are given in the lab. The goal is to enable students to learn the essential techniques of multitasking operation with Digital Signal Processor (DSP) and C/C++ programming for real-time computing, data acquisition, and digital control in a period of two weeks. The high-speed processing of the DSP allows a good approximation of a continuous-time system and permits the effect of sampling time to be considered.

The second part of the laboratory practice requires the students to complete a term project that has been proven to be a major creative enterprise. In each project, the C-code for the controller algorithm has been written in Simulink C-code generator and downloaded to a dSpace DSP chip running in the background of the host PC. The vision system has its own DSP chip running C-code written by the user to relay the feedback to the host. The real-time control system is implemented on a dSpace DS1102 controller board, with a FIVS as a feedback sensor, and the Intel486-66MHz PC in the Campus-wide CIMS Intelligent Mechatronics Laboratory. The experimental setup includes a Windows-MATLAB, Control Toolbox, and Simulink C-code generator.

Students model the physical system, and use the MATLAB and toolboxes to design a controller to stabilize the system. The resulting control law will then serve as input to the interactive program for closed-loop animation and testing. In order for the students to focus their attention on the project, the SIMULINK C-Code Generator is provided. This generates C-code for the control system that has been modeled using Simulink block diagrams. Students can interface the code directly to hardware for real-time testing. Previously, the students have had to write C-code manually, a time consuming process that often resulted in new bugs. The direct linking of code into a real-time testing environment will facilitate rapid prototyping. Figures 3 and 4 illustrate a sample student project where a creative multiprocessor-control digital vision system was used as a combined feedback and controller element to regulate a ball on a balancing beam.

The availability of several graduate assistants with different academic background provides the instructor unique opportunity to give students experience with projects beyond traditional laboratory exercises on automation, control, or robotics. As demonstrated in Reference 8, where a prototype real-time vision-based tracking control of an unmanned vehicle was developed in the IML, the collaborative environment permits the students to have the hands-on experience in integrating mechanical engineering, electronics, digital control, and image processing into their design, development and implementation processes in a quarter-long course. Through demonstrating the concept feasibility of a complete autonomous prototype, the students have gained not only significant insights in implementing a relatively complex system, but also confidence in their ability to solve a real-world digital control problem in a multi-disciplinary team.

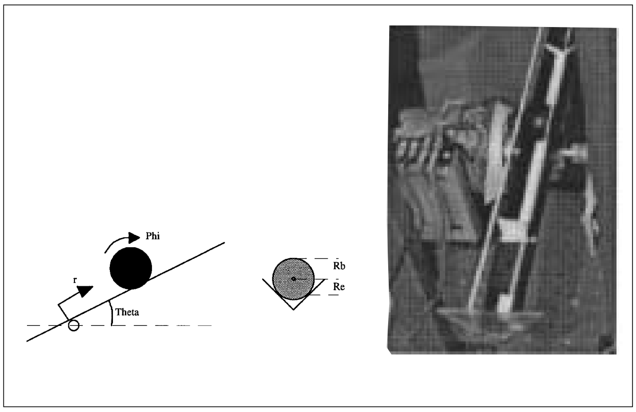

Figure 3. Schematics illustrating the ball-on-beam experiment.

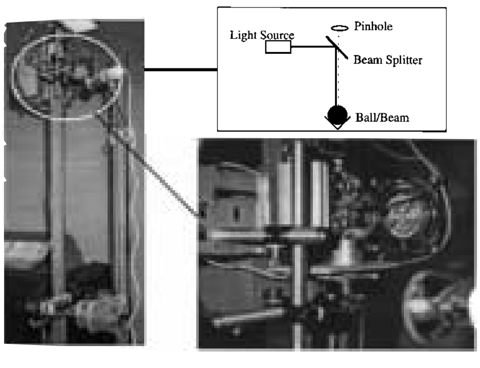

Figure 4. Prototype experimental setup.

B. An Interdisciplinary Project: Multiagent Robotics

The Intelligent Mechatronics Laboratory provides a fertile ground not only to support classroom instruction but also to encourage extracurricular interdisciplinary projects. An excellent example of this type of effort involved a student team entry in the 1994 American Association for Artificial Intelligence's Mobile Robot Competition.[10]

Georgia Tech Team members had varied backgrounds in computer science, electrical, mechanical, and aerospace engineering. The competition's goal was to create a robotic system capable of moving around within an office environment, picking up trash and depositing it in wastebaskets. Our team constructed a three robot team: Io, Callisto, and Ganymede (Figure 5). Each was equipped with a vision system and manipulator. They were all built from the ground up using resources available in the Intelligent Mechatronics Laboratory.[11]

After completion and testing, funds were obtained from the competition sponsors for student travel to Seattle where the event was held. Our team was victorious and demonstrated successful retrieval of soda cans using a multirobot approach.

This project was valuable from several standpoints:

- it gave students experience in interdisciplinary teams, each drawing upon other team members' expertise;
- it provided an opportunity for them to operate in a largely unsupervised environment, honing their management and organizational skills; and
- it developed a solid esprit de corps providing some relief from the long road of graduate study.

Some unexpected difficulties were encountered related to the location of the lab. We found that physical proximity is a very important factor for faculty and student participation. A close examination of the course listings shows that electrical engineering is missing. This is because, the School of Electrical Engineering is physically far away from the Manufacturing Research Center, where the lab is located. Nonetheless, participants from several other disciplines across the campus felt it well worth the trip to include exercises in the laboratory. It may be desirable in the future to set up a laboratory annex at a site more closely situated to the School of Electrical Engineering. If this were to happen, with the possible shuttling of equipment between sites and a high-bandwidth network connection, it is likely there would be more participation from that unit and perhaps participation from even more units.

A key enabler for the development of the IML was the existence of an interdisciplinary manufacturing education program — CIMS. CIMS had a well-established track record at Georgia Tech, and was the forum for the discussion of a shared lab. CIMS also provided the platform for dealing with all the entities involved in creating the IML, including the AT&T Foundation, local AT&T plant personnel, Georgia Tech administration, individual academic units, and faculty.

The conclusion, we believe, is clear. There is a great opportunity for leverage through lab sharing. The key to exploiting this opportunity is for relevant faculty from various academic units to be willing to shed their traditional disciplinary armor and work together.

V. Concluding Remarks

We believe that the Intelligent Mechatronics Lab is an ideal interdisciplinary laboratory for technical electives at Georgia Tech in several ways. First, the students receive hands-on experience in support of lecture instruction that was not economically possible before. Second, it is eye-opening for students, simply by exposing them to experiments and joint efforts with students and faculty from different disciplines. Third, components of lab exercises developed in one course can often be used in another course. In such cases, there is tremendous savings in development time for faculty and students. A side benefit is that the lab assistants gain hands-on experience as well as instructional capabilities.

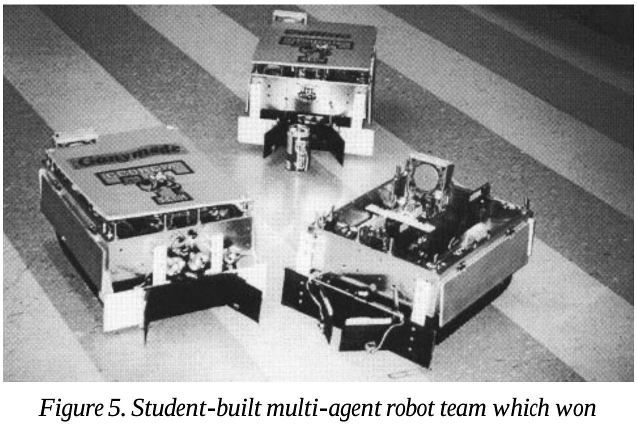

Figure 5. Student-built multi-agent robot team which won the 1994 AAAI mobile robot competition.

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