Robotics, Microcontroller, and Embedded Systems Education Initiatives at the University of Georgia An Interdisciplinary Approach

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This paper reports on four microcontroller-based courses developed at the University of Georgia for a broad multidisciplinary undergraduate and graduate student body. The courses are Introduction to Robotics, Embedded Systems, Introduction to Microcontrollers, and Advanced Microcontrollers. These courses which are taught in a hands-on manner equip students with the necessary tools and know-how to make use of the powerful technology of microcontrollers within their own disciplines. The paper addresses some of the challenges encountered due to the diverse student backgrounds and how these challenges are met through various pedagogical methods such as team work, achieving the right balance between theory and practice, and giving students from various disciplines an "industry like" experience.

INTRODUCTION

Control engineering practice has evolved rapidly with the proliferation of fast computers on a chip. Additionally, the use of microcontrollers and embedded systems has become inevitable in almost every field. An area that has traditionally been reserved for electrical or mechanical engineers is now multidisciplinary integrating digital electronics, communications, and computing with a variety of systems ranging from medical to biological to environmental. Given these developments, microcontroller and embedded systems education has been witnessing significant changes over the past few decades. From project oriented courses that emphasize real world applications, to the proliferation of new educational tools such as robot kits, the new trend is to take this area beyond the traditional engineering setting and to make it accessible to students from various disciplines in a way that would foster their practical understanding and use of it. This paper describes efforts at the University of Georgia to make microcontrollers, embedded systems, and robotics education available to undergraduate and graduate students from a wide range of scientific disciplines.

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The University of Georgia hosts a new model of engineering education where traditional disciplines have given way to a new kind of engineering designed to capture the convergence of various disciplines. Unlike conventional engineering programs, this innovative interdisciplinary approach provides the opportunity for new types of engineering courses, educational approaches and programs which lead to students with a broader understanding of engineering who are capable of engaging in careers devoted to the integration of advances from various disciplines.

Within this interdisciplinary engineering environment, four courses have been developed at the University of Georgia to meet the demands and challenges of a diverse student body in the area of microcontrollers, embedded systems, and robotics education. In this paper, we describe these courses and discuss their content, the target student audiences, and the underlying pedagogical approaches used particularly in integrating practical laboratory experience with theoretical classroom material. The courses are widely disseminated to students from diverse backgrounds including those with non engineering or non traditional engineering backgrounds and they do not assume a prior knowledge of hardware or programming. All courses combine important aspects of theoretical knowledge with practical experience fostered through hands on projects and an intensive team-based lab experience. The four courses are: Introduction to Robotics, Embedded Systems, Introduction to Microcontrollers, and Advanced Microcontrollers.

INTRODUCTION TO ROBOTICS

This course is geared toward junior/senior level undergraduates and beginning graduate students in computer science and artificial intelligence (the University of Georgia offers BS, MS, and PhD degree programs in computer science as well as a separate MS degree program in artificial intelligence). The primary focus of the course deals with all aspects of autonomous mobile robots. In particular, the major issues investigated are cognitive behavior, and motion. Cognitive behavior addresses problem solving using sensory inputs and desired goals. Motion deals with aspects of movement in the real world from simple fixed-base robotic arm movement to autonomous rovers in unknown environments.

Students completing the *Introduction to Robotics* class will have been exposed to a number of lecture topics as well as many practical (hands-on) topics. Lecture topics include introduction to robotics, cybernetics, history of robotics, robotics in fact and fiction, application areas, mechanical foundations, electrical foundations, control, intelligent behavior, autonomous robot architectures, robot reasoning, knowledge representation, and planning. Practical topics include robot kit construction, wiring diagrams, simple circuits and components, basic electronics, soldering, motors, gears, principles of motion, microcontrollers/microprocessors, sensors, feedback, and computer programming for intelligent behavior. The course consists of traditional lecture activities and hands-on laboratory activities [1, 2, 3, 4, 5, and 6].

Performance measurement within the class is based in part on traditional assignment/testing instruments. However, the majority of a student's grade is based on laboratory exercises. Laboratory reports are prepared by teams of three to five students working to resolve a specific laboratory challenge. Each challenge is designed to achieve an educational objective involving mastery of various robotics related topics, problem solving creativity and innovation, team organization and management, and verbal and written presentation skills. At a more detailed level, each challenge provides students with ample opportunity to become immersed in the mechanical and behavioral aspects of the various robots used in the class. At a more abstract level, students are exposed to a simulated work environment (as close to a real-world environment as possible) where a team is given the task of achieving a specific goal within a specific time frame while using available tools and equipment. Performance is based on results not effort, on quality of team output not on the superiority of work done by any one individual. Since the challenges are team-based, a mechanism is in place to translate a team "grade" into an individual grade for each of the students on a team. This mechanism ensures that credit is given to those members of the team who earn and deserve it.

The major laboratory exercises, called challenges, require the student teams to design and build their robots to exhibit some specific behavior ranging from simple motion to sophisticated real-time problem solving. Examples of these challenges include the "square figure eight" challenge, the "maze egress" challenge, and the "honey bee" challenge. The basic robotic equipment available to each team includes various sensors, batteries, two motors, an electronic module, a chassis with wheels, and miscellaneous supplies.

The square figure eight challenge allows each team to become familiar with the software and (robotic) hardware. The task is simply to develop a mobile robot that can start from a known position (the home position), move one meter forward, turn 90° to the right, move one meter, turn 90° right, move one meter, turn 90° right, move two meters, turn 90° left, move one meter, turn 90° left, more one meter, turn 90° left, move one meter, and end up back at the home position. As most of the students in the class have strong computing backgrounds, the software portion of this challenge is quite simple. The major problems they encounter deal with the hardware portion of the challenge, especially synchronizing the motors for proper straight-line motion and accurate turning, and calibrating the robots for the proper distance movement. Students quickly learn to solve these problems by analyzing the relationships between power drain (due to sensors, motors, electronic components, wheel material and floor covering) and the power supply (rechargeable batteries).

The "maze egress" challenge requires each robot to exit a maze in a short amount of time. By the time the class is ready for this assignment, the challenges have evolved into competitions among the teams. The challenge "winner" in this case is the team whose robot can exit the maze in the shortest time (maze configuration is random and unknown to the teams prior to egress demonstrations). The behaviors involved in maze egress include reactive behavior, selective random motion, and some small amount of learning. Typically, infrared range sensors and touch sensors are the primary sources of inputs to the robots for this challenge; however, some creative teams include interesting distance measurement schemes as well as some sort of terrain mapping memory scheme. The maze is constructed on a large conference table and has an outer boundary wall as well as internal passageways. The internal wall configuration disallows naïve maze egress schemes such as simply following the left-hand wall until an exit is reached. From a resource supply and resource usage point of view, students quickly learn which ideas work best for the various situations their robots encounter. For example, they learn to develop robot behaviors that "recognize" blind alleys that require the robots to back up rather than turn around, non-productive repetitive movements such as being "stuck" in an infinite reaction loop, and remembering previously visited passageways that did not lead to an exit.

One of the more difficult challenges is the "honey bee" challenge. The basic idea has a robot (a honey bee) leaving from a home base area (the hive), searching a limited terrain for a specific target (the flower), returning to the home base following the shortest path, and communicating the location of the target to another robot (fellow gatherer) so that the other robot can then move directly (via the shortest path) to the target. Various obstacles are randomly placed throughout the terrain in order to impede the robots. Initially, students find this challenge quite daunting. However, this is soon overcome with a little research and imagination. For example, they learn to take advantage of the terrain features by using the obstacles as landmarks to aid the search and recovery tasks (just as honey bees take advantage of landmarks to guide their foraging). This aids with mapping the terrain so that the robot will be able to determine the shortest path back to the home base area. Lessons learned during the earlier challenges are incorporated within this challenge as well. Searching the terrain for the target is facilitated by behavior implemented in the "maze egress" challenge. The portion related to communicating the location of the target to another robot is the area where the students really come through with creative and ingenious solution methods. The typical scheme is usually based on sending and receiving a type of Morse Code using the infrared emitters of one robot and the infrared detectors on another robot.

Each team has a variety of equipment available to use for developing their robots. Kits provide the primary source of equipment (although each challenge is assigned a specific kit, students are given broad latitude when it comes to creative hybrid designs). Examples of kits available to the teams include: Boe-Bot kits from Parallax, Lego Mindstorms kits, Botball kits from the KISS Institute for Practical Robotics, Hexapod Walker kits from Lynxmotion, and Palm Pilot Robot Kits (PPRKs) from Acroname. In addition, a variety of supplies, parts, electronics, and fabrication items are available. Each kit has certain special features and characteristics, as well as similarities. For example, each kit except for the Lego kits use servos for the drive motors (the walker legs are driven by servos), each kit uses some sort of infrared sensor and touch sensor to gain inputs from the environment, and each kit is controlled by programs developed on a PC using a development environment. The programming languages used to code robot behaviors vary and are dependent upon the type of microcontroller used in the kits. The table below shows the kits along with their corresponding microcontroller and programming language environment. Note that the Hybrid items are not kits but are simply collections of parts and supplies using various components. The BrainStem module is a special component from Acroname.

Kit	Microcontroller	Programming Language
Lego Mindstorms	RCX (Hitachi H8 series)	NQC (not quite C)
Boe-Bot	BasicStamp (PIC16C57)	P-Basic
Hexapod Walker	BasicStamp (Scenix SX28AC)	P-Basic
Botball	HandyBoard (MC68HC11)	Interactive C
PPRK	SV-203 (PIC16C78B)	C (CodeWarrior for Palm)
Hybrid-1	BrainStem (PIC18C252)	C, C++, Java
Hybrid-2	HandyBoard (MC68HC11)	Interactive C
Hybrid-3	BasicStamp (PIC16C57)	P-Basic

Although students in the *Introduction to Robotics* course do not directly program their microcontrollers using assembly language programming, they do become very familiar with handling digital and analog sensory inputs along with controlling servomotors using pulse width modulation. Hobby servos and standard DC motors are the devices of choice for locomotion. Sensors available for use include: touch/switch sensors, light/photocell/phototransistor sensors, infrared (modulated/unmodulated) sensors, compass sensors, ultrasonic ranging sensors, and thermal sensors. Hybrid component design and any necessary construction usually take place in the Microelectronics Lab within the Artificial Intelligence Center. Students have access to soldering equipment, test instruments, and other miscellaneous items.

Before teaching this course as a regular course in the curriculum, it was first tested as a trial independent study course for graduate students. Since then, the course has become a regular fixture in the fall semester offerings. Interest in the course is very strong among students from several departments outside of computer science as well as within the department. Word of our robotics activities has attracted local and regional news coverage, and requests for visits from many area middle and high schools.

EMBEDDED SYSTEMS COURSE

This course is offered by the department of Computer Science and is targeted at upper level students in this program as well as non-Computer Science students. The basic idea of this course is to introduce the students to Embedded Computing in general, familiarize them with various off-the-shelf components, and to have them build some actual working systems. The biggest challenge in this course is in coping with the diverse backgrounds of students. Most have no or only cursory hardware-related background, and therefore a fairly in-depth review of electrical physics is necessary before students are ready for the course material.

For the most part, students were expected to learn by building working systems in hands-on labs. However, there were a number of important topics that were treated in a lecture or tutorial setting. Students were given a tour of the lab facilities and shown each of the components that would be used throughout the semester. They were introduced to part numbers and datasheets and became familiar working with them. In depth tutorials were given on proper use of the oscilloscope, electrical safety issues, wire wrapping, soldering, and printed circuit board (PCB) manufacturing.

The PCB manufacturing tutorial seems to be of particular interest to students. This begins with an overview of the manufacturing process, and each individual stage (i.e., Etch resist, etching, drilling, assembly etc.). Other processes such as UV etching are also discussed. The process demonstrated in class begins with a double sided copper-clad. Etch resist is applied using a Dalo pen, then etching is performed using a Ferric Chloride solution, followed by cleaning and drilling. There are many ways to improve this tutorial that will be considered in future iterations of this course.

Before students are able to complete fairly large (by undergraduate standards) design projects, they must have a detailed knowledge of the available components. During this stage of the course, a number of labs were designed to introduce the various components and prepare students to work with them during the project design phase. These components included an accelerometer, an analog to digital converter (A2D), a digital to analog converter (D2A), a digital signal processing chip (DSP), and a field programmable gate array (FPGA).

In the accelerometer, A2D, and D2A labs, students were simply responsible for connecting the component on a solderless breadboard, supplying the appropriate input and probing to observe the output. This was not trivial since these are analog components requiring resistor tuning, and often a complicated power supply.

In the DSP lab, students were given a Texas Instruments evaluation module (specialized PCI card) and asked to write some software, compile it with the TI tools, and then optimize it for performance. Students were graded based on the correctness of their results and the level of optimization they achieved.

In the FPGA lab, students were responsible for implementing an incrementer on a reconfigurable device. They developed a hardware description language (HDL), compiled it using our Altera tools, programmed a reconfigurable device, and then breadboarded and tested the system.

In addition to laboratory exercises, students were also asked to complete two course projects and these were highly emphasized in the overall course grading. In the first project, all students were required to implement the same assigned system. The students were allowed to choose their own final project.

In the first project, which is based on a similar course at Michigan State University, students were given the task of controlling the position of a ping pong ball in a vertical tube by modifying the speed of a fan at the base of the tube. Position information is provided to the system by a series of photocells illuminated by a light source. The idea is that when the ping pong ball is at a certain position, it will occlude the light source, which in turn can be observed on the photocell. The students were required to prototype this system, including developing a finite state machine to control a power transistor driving the fan.

The second project was left open-ended to the students. They were allowed to select any suitable system (with oversight for safety and difficulty issues). This project was intended to give the students experience in designing an entire embedded system from the ground up.

There are a number of important refinements that should be made to the course and new topics that would be interesting to cover in future semesters. In terms of refinements, expanded coverage of PCB manufacturing would be of interest to the students. Also, it would be helpful to look into less complicated analog components and other components with simpler packages (some components were non-DIP). Several new topics could also be integrated into the course. These could include an introduction to signal processing, high speed communications/error correction, and compression techniques.

INTRODUCTORY AND ADVANCED MICROCONTROLLERS COURSES

The two courses previously described are concerned with giving students a broad experience with microcontrollers and they enable them to handle complex control problems in robotics and other types of applications using off-the shelf hardware and software modules. The two microcontroller courses described below give students a deeper, more focused experience with the microcontroller within the context of fairly complex monitoring control problems. These two courses which have been developed by the Department of Biological and Agricultural Engineering at the University of Georgia are both split-level (undergraduate and graduate) and although they primarily target students in the department, they attract students from various disciplines. In particular, these courses serve as electives for computer science students to fulfill requirements of a dual computer science/engineering certificate, as well as graduate students from many scientific disciplines such as physics, and forest resources.

The introductory microcontroller course follows the traditional course/laboratory format. Assembly programming is taught gradually throughout the course and focus is placed on how to use the chip to solve particular monitoring problems instead of chip architecture. The first lab is a tutorial which gets students familiarized with the software and hardware aspects of the microcontroller development environment which is centered around a Motorola 68HC11 evaluation board (EVB). The Motorola microcontroller was chosen due to the extensive extent to which supporting material and development tools have been developed for this chip and since it is one of the most used chips in industry. Next, students get familiar with the HC11 simulator also provided by Motorola (AVSTM). This software package is important since it is an excellent debugging tool and an effective way of visualizing the chip architecture. In the next lab exercise, students experiment with the various input and output digital ports of the HC11 by reading switches and sequencing light emitting diodes (LEDs) on the target board. Next, students become familiar with a range of utility subroutines provided by the EVB monitor program and learn how to incorporate them in their own programs. At this point, most students have learned some basic assembly programming and are capable of writing more sophisticated software programs.

For the next step, students develop a program and build the hardware interface for a four-column by four-row alpha-numeric matrix connected keypad to the HC11 using program driven polling. Students develop modular and complex programming skills and improve their hardware and software debugging skills in this lab. Similarly, students interface a Varitronix 20x4 LCD module to the HC11. The LCD has an on-board HD44780 Hitachi microcontroller and therefore, students learn how to interface the HC11 with another microcontroller embedded in another device. The last and most significant lab in this course deals with analog data acquisition. In particular, students monitor temperature of a water bath using the HC11. Students learn how to program the A/D converter on-board the HC11 and they get the opportunity to build the necessary signal conditioning circuitry for interfacing the temperature sensor (AD590) with the microcontroller.

In the introduction to microcontrollers course, students acquire the necessary background to utilize the microcontroller as an embedded monitoring device. The next step is to teach students the real-time features of the microcontroller and to integrate this practical knowledge into a real-world project. Therefore the Advanced Microcontrollers course is built around real engineering monitoring and control problems and the advanced features of the microcontroller are taught through a top-down problem solving approach. At the beginning of the term, a group project is presented and a solution strategy to the monitoring and control problem at hand is developed by each group using the different functions of the microcontroller as building blocks. The most relevant aspects of the solution are broken down into smaller tasks and assigned as laboratory exercises. Lecture time is allocated as students encounter a road block and realize the need for a new feature of the microcontroller or a new concept or body of knowledge to solve the problem at hand. Focus is kept on the final outcome of completing the project at hand which keeps all group members engaged and eager to learn the next step that would help them move ahead with their projects.

An example project in this course deals with controlling the speed of a small DC motor using the Motorola 68HC11 microcontroller's timing system and using Pulse Width Modulation (PWM) with feedback. In dealing with motor speed measurement, students are made aware of the various sensing options available and the pros and cons of each option. Signal conditioning techniques are addressed for each type of sensor chosen. The resulting pulse generated as the motor turns is used as input to the microcontroller and students are therefore introduced to the input capture feature of the HC11 timer system and its use to measure the duration of external events. Through this process students also get introduced to the microcontroller's pulse accumulator and to real-time interrupts. Measurement accuracy and resolution are introduced and averaging techniques are used to filter out the noise.

The next step in this project is the implementation of Pulse Width Modulation (PWM) with motor speed feedback to control the motor. First students are introduced to the concept of PWM and how it can be used for open loop control. They also learn how to modulate a pulse using the timer's output compare functions. Then they get introduced to the concept of feedback to obtain a more stable target speed. A significant portion of time is spent studying the interface circuitry required between the motor and the microcontroller. Students get introduced to optical isolators, power supply requirements and the concept of interfacing low-level logic with inductive loads through power transistors.

For a detailed description of the two microcontroller courses, the history behind their development, the pedagogical approaches followed, and detailed laboratory assignments, the reader is referred to [7] and [8].

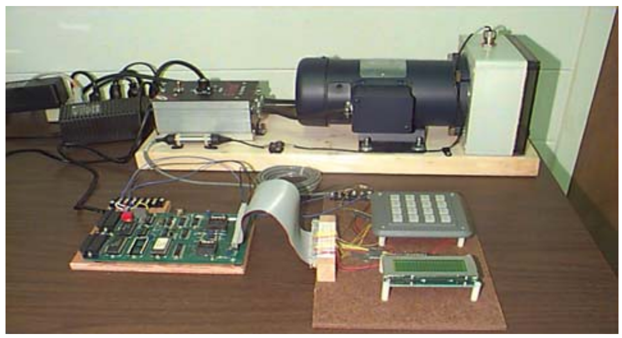

Fig. 1. Student Prototype Microcontroller Station for Motor Speed Monitoring and Control

CONCLUSIONS

In this paper, we described four microcontroller-based courses offered at the University of Georgia to undergraduate and graduate students from various disciplines. The courses do not assume prior knowledge of software or hardware and they all follow an applied hands-on approach. The courses take complimentary pedagogical approaches and collectively, they give our students the necessary background to make effective use of microcontrollers within their own disciplines. Whereas the embedded systems and Robotics courses are concerned with embedded systems in a broad sense and handling complex control problems in robotics and other types of applications using off-the shelf hardware and software modules, the introductory and advanced microcontroller courses give students a deeper, more focused experience with the microcontroller within the context of fairly complex monitoring control problems. About 80 students per year enroll in these courses which are offered once a year. Feedback from students who have taken these courses has been excellent.

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Captions

Fig. 1. Student Prototype Microcontroller Station for Motor Speed Monitoring and Control