Using Robotics to Teach Integrated System Design via Multidisciplinary Teamwork

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Real-world systems are generally comprised of interdependent components creating complex integrated systems. These systems are developed by cross-functional or multidisciplinary teams with members bringing expertise from different fields. The goal of this project is the development of a comprehensive undergraduate course in robotics that encompasses various fields of engineering that are integral to robotic systems: Computer Science, Electrical and Computer Engineering, Mechanical Engineering, and Industrial Engineering. The pedagogical goals of the course include providing hands-on learning in practical robotics and integrated system design, as well as direct experience with group dynamics by means of interaction with people in multidisciplinary teams. Descriptions of the course and the hands-on lab assignments are presented along with a thorough course assessment.

Categories and Subject Descriptors: K.3.2 **[Computers and Education]**: Computer and Information Science Education--*Accreditation, Computer science education*; I.2.9 [**Artificial Intelligence**]: Robotics--*Autonomous vehicles, Kinematics and dynamics, Manipulators, Sensors*

General Terms: Design

Additional Key Words and Phrases: Robotics, sensors, manipulators, kinematics, feedback control, localization, navigation, multidisciplinary, cross-functional, teamwork.

1. INTRODUCTION

The curriculum in any specific area of study tends to narrowly focus students on that area, whereas real-world complex systems tend to integrate components from multiple disciplines. The development of such systems has shifted from designing individual components in isolation to working in cross-functional or multidiscplinary teams that encompass the variety of expertise needed to design an entire system [Rosenblatt and Choset 2000; Brockman 2001; Hartfield 1996]. This means that students must learn the team building and communication skills to work with others outside of their own discipline. The Accreditation Board for Engineering Technology (ABET) recognizes the importance of these abilities in its *Criteria for Accrediting Engineering Programs*: “Engineering programs must demonstrate that their graduates have an ability to function on multi-disciplinary teams” [Engineering Accreditation Commission 2000; Aldridge and Lewis 1997]. The study of robotics provides an excellent instrument for teaching and learning about working in multidisciplinary teams.

Robots are complex integrated systems comprised of interdependent electrical, mechanical, and computational components. They afford a view of information processing from the microprocessor level up through the application software, providing an excellent illustration of the connection between mechanical, electrical, and computing components. Furthermore, robots are a physical embodiment of computational processes. The connection of robotic physical actions to more abstract computation creates effective feedback for learning [Jadud 2000; Papert 1980; Fagin 2000]. Because of the variety of concepts that robots engender, they have become a valuable tool for teaching the practical, hands-on application of concepts in various engineering and science topics [Beer et al. 1999; Norstrand 2000; Avanzato 2000; Meeden 1996; Kumar and Meeden 1998; Gaines and Balac 2000; Fagin 2003; Klassner 2002]. The multidisciplinary character of robots makes them a natural focus of study for teaching and experiencing teamwork that includes members from cross-functional vocations.

The overall goal of this project is the development of a comprehensive undergraduate course in robotics that emphasizes multidisciplinary teamwork by encompassing many of the diverse fields of engineering which are integral to robotic systems: Computer Science (CS), Electrical and Computer Engineering (ECE), Mechanical Engineering (ME), and Industrial and Manufacturing Engineering (IME). This is a two-year project supported by a grant from the National Science Foundation's Division of Undergraduate Education under the Course, Curriculum, and Lab Initiative – Adaptation & Implementation Program. The course adapts curriculum material from CMU's General Robotics Course [Rosenbatt and Choset 2000; Choset 2003], from Swarthmore University's and Bryn Mawr College's Robot Building Laboratory Project (NSF CCLI Grant #9651472) [Kumar and Meeden 1998], from Drexel University's Research and Education Tools for Low-Cost Robots (NSF CISE Grant #9986105) [Greenwald and Kopena 2003; Greenwald 2001], from Bucknell University's Catalyst Team on Teamwork (NSF Grant #9972758) [Csernica et al. 2002], and from Southern Illinois University Edwardsville's Laboratory Experience for Teaching Participatory Design (NSF CCLI Grant #9981088) [Weinberg and Stephen 2002].

The course is cross-listed for credit to students in CS, ECE, ME, and IME. It incorporates team-based robotics projects in which the teams are cross-functional and composed of one student from each area. The pedagogical goals of the course include:

1) To provide a hands-on experience in practical robotics
2) To learn about integrated system design
3) To learn to interact with people in different disciplines in a cross-functional team
4) To learn about group dynamics and teamwork

This paper presents the outcome of the first offering of the course. For the first year, the course was taught by a team of faculty members from all of the represented areas. Emphasis was placed on cross-functional teamwork aspects, including the development of materials in each area as applied to robotics that was accessible to all of the students regardless of their majors and the development of robotics lab assignments that emphasized the multidisciplinary teamwork necessary for designing integrated systems. An eventual goal of the project is to adapt the materials so that the course can be taught at undergraduate institutions that do not offer a degree in robotics, an active robotics research center, or even the full range of engineering expertise that is represented in such a comprehensive course. Informed by the assessment of the first year presented in this paper, material will be further developed to allow the course to be taught by a single faculty member.

2. COURSE ORGANIZATION AND TEAMWORK

The course, entitled “Robotics: Integrated System Design”, was offered for the first time in Spring 2004 as a senior-level elective in all four majors: CS, ECE, ME, & IME. Enrollment limits were used to achieve a balanced enrollment between the majors for the purpose of team formation. Twenty-nine students enrolled in the course: eight from CS, eleven from ME, and ten from ECE (six Electrical Engineers and four Computer Engineers). Following the guidelines put forth in “Practical Guide to Teamwork” [Csernica et al. 2002], nine teams were formed using the criteria of major, availability, and grade point average. To ensure that teams were multidisciplinary, each team was assigned at least one student from

CS, ME, and ECE (one team had a Computer Engineer in place of a Computer Scientist). On the first day of class, students completed a survey that included a request for the times during which they were available for team meetings. The amount of face-to-face meeting time is important for successful teamwork [Pinto and Pinto 1990; Ruekert and Walker 1987; Song et al. 1997], so availability was the second criterion used to formulate teams. To ensure that all teams would have an equitable distribution of skill levels, grade point average was used as the final criterion.

The schedule of class topics is presented in Table 1 (detailed information and materials can be found at http://roboti.cs.siue.edu/classes/). The general topics covered were:

- Control Theory: forward & reverse kinematics, feedback control
- Sensors: circuits and signal processing, simple computer vision
- Artificial Intelligence Control: localization, planning
- Multiple Robot Coordination

Week	Day 1	Day 2
1	Introduction to Robotics	Teamwork and Group Dynamics
2	Robot Technical Fundamentals	Forward and Inverse Kinematics
3	Forward and Inverse Kinematics	Introduction to the Handy Board
4	Feedback Control	Feedback Control
5	Electronics Primer and Sensor Fundamentals	Circuits
6	Sensor Operating Principles	Advanced Sensors and Signal Processing
7	ME and ECE Quiz	AI and Reactive Control
8	Computer Vision and Image Processing	Localization, Navigation, and Planning
9	Localization, Navigation, and Planning	Localization, Navigation, and Planning
10	Problem Analysis and System Design	Final Project Assignment
11	Multi-Robot Coordination	Multi-Robot Coordination
12	Algorithmic Time and Space Complexity	Robot Competitions
13	CS and IME Quiz	Final Project Trouble Shooting Day
14	Final Project Presentations	Final Project Presentation
15	Final Project Demonstrations	Final Project Demonstrations

Table 1: Schedule of Class Topics

The topics were ordered using a layered abstraction approach [Crabbe 2004], beginning at the lowest level of information, where relative position is used to determine movement (kinematics), proceeding to the attribute layer, where sensor input is processed to determine situations (behavior-based robotics), and finishing at the model layer, where abstractions of the world are used to make planning decisions.

Coverage of each topic area included some basic concepts of the respective discipline in order to provide students outside of that discipline with a sufficient framework for understanding the more advanced concepts. To mitigate the potential for disinterest and boredom caused by presenting basic concepts to students within their respective discipline, concepts were covered from the perspective of their application to robotics.

The grading policy was set to emphasize the hands-on, team-based aspects of the course. However, a significant amount of the grade was set aside for quizzes and the final examination to ensure that students made a sincere effort to learn concepts from disciplines that were complementary to their own:

- Team Lab Assignments: 25%
- Team Final Project: 30%
- Quizzes: 25%
- Final Examination: 20%

To enhance the multidisciplinary teamwork aspects of the course, students were encouraged to utilize their lab project teams to form study groups for the quizzes and the final exam in order to more directly learn about each other's discipline. Although this aspect of the course was not specifically tracked or formalized (as suggested in [Csernica et al. 2002]), both single teams and multiple teams were observed studying together in the lab prior to the quizzes and the final exam.

On the day that the teams were announced, lecture material and in-class exercises were presented to emphasize how teams work and how team members may interact within their group (group dynamics)

[Csernica et al. 2002; Beyer and Holtzblatt 1998; Weinberg and Stephen 2002]. The specific topics included:

- What defines a team?
- Team process: team roles, decision making, conflict resolution
- Team roles: Chief Technical Officer, Scribe, and Rat Hole Watcher
- How to run an effective team meeting
- Characteristics of good and bad team members
- The difference between constructive and destructive criticism
- Individual personality types and their impact on how individuals work and interact
- Brainstorming methods
- Creative thinking and potential mental blocks to creativity

when teams were announced the students were asked to relocate their seating to be with their teammates. During the in-class exercises, the teams were instructed to practice the same team process they were expected to use during their own team meetings. This included assigning team roles, setting a meeting agenda, and recording meeting results. The identified team roles were Chief Technology Officer (CTO), Scribe, and Rat Hole Watcher. The CTO is the identified leader of the project, this role was expected to rotate between team members based on the emphasis of the particular lab assignment. For example, if the assignment's focus was a mechanical engineering topic like kinematics, then the teammate majoring in ME would be the CTO. The Scribe is responsible for recording the results of the each team meeting. Team minutes were required to be submitted as part of the grade for each assignment. Finally, the Rat Hole Watcher is the person empowered to stop a line of conversation that is off topic. Discussions can quickly move from one topic to the next, leading to topics that are not even related to the actual project or class. The responsibility of the Rat Hole Watcher is to call a halt to non-relevant lines of discussion and to put the meeting back on topic.

The choice of robotics platforms for the team lab assignments and projects included LEGO mechanical pieces and the Handy Board Controller (www.handyboard.com) [Martin 2001]. This platform was chosen for its mechanical flexibility, its ability to easily interface with custom-built sensors, the availability of a C development environment (IC: Interactive C), and the availability of a low-cost color camera, the CMUcam (www-2.cs.cmu.edu/~cmucam/). While there are instructions available for building sensors and interfacing motors (see, for example, [Kumar and Meeden 1998; Martin 2001; Greenwald 2001]), robot kits developed by the KISS Institute for Practical Robotics were purchased (www.kipr.org). Each kit cost $1245 and included a vast amount of LEGO pieces, geared and servo motors, a variety of pre-built sensors, a CMUcam, a Handy Board, and a LEGO Robot Controller (LEGO RCX). Purchasing these kits significantly reduced the amount of effort needed to prepare and organize the kits, although one graduate student was hired to help manage the robot kits, to provide expertise to the teams as needed, and to help develop demonstration robots for the class. Fifteen robot kits were purchased with the anticipation of having ten student teams, two kits available for developing demonstration robots, and the remaining kits available for replacement parts. In addition to the robot kits, electronic parts were purchased for labs that required the development of custom sensors as discussed in Section 3.

3. HANDS-ON LABORATORY ASSIGNMENTS

The general philosophy and expectations of the hands-on robotics projects for this class are provided in Table 2. The lab assignments provide an opportunity to directly interact with the technology, as well as an opportunity to design, implement, and experiment with the various concepts that they embrace. This approach to teaching creates an active learning environment in which students can explore a significant design area, make hypotheses about how things work, and conduct experiments to validate their assumptions [Jadud 2000; Papert 1980; Turkle and Papert 1992; Miller et al. 2000]. Seymour Papert termed this style of learning “constructionism” [Turkle and Papert 1992]. For this course, the overall philosophy of the lab assignments is to provide a hands-on, multidisciplinary design experience that complements the lecture material. In this way, it creates a type of "directed constructionism" learning experience in which students are asked to explore related topics in a specific order [Papert 1980; Rosenblatt and Choset 2000].

General Lab Philosophy & Expectations
• Lab assignments provide hands-on experience applying the concepts covered in lecture to elements of robotics.
• Lab assignments prepare each team for the design and implementation of the final project.
• The assignments are designed to assist in the development of effective teamwork skills.
• The lab assignments provide an opportunity for students from various disciplines to learn enough about the disciplines of their teammates to be able to effectively work on multidisciplinary projects.
• Lab work is team-assigned and must be performed as a team; teams are expected to meet, discuss, plan, and develop the labs **as a team**.
• Team meetings are to be conducted as discussed in class; each team member should be assigned a specific role, each meeting must have an agenda, task assignments must be specified, and progress must be documented.
• Team roles must be assigned appropriate to the topic. The Chief Technical Officer (Facilitator) will be the person with the appropriate background; for example, an assignment on circuits will be led by an electrical engineer. The other positions assigned will be Scribe and Rat Hole Watcher (Timer).
• With each assignment, teams will submit their team meeting minutes. Minutes must include a list of attendees and assignments that were made, a full description of what was discussed and accomplished, and an indication of the meeting's duration. Minutes must be word-processed and shall be graded for professionalism and detail.

Table 2: Expectations of Lab Assignments

3.1 Lab Assignment 1: Rube Goldberg Machine

The first lab assignment involved the design and implementation of a Rube Goldberg Machine (See www.rgmc.com) that would capture a mouse without harming it (see Figure 1). The goals of this assignment were:

- To familiarize the students with the building materials in the robot kit.
- To help each student achieve an engineering frame of mind for designing and building.
- To provide students with an initial team-building exercise.

The machine was required to consist of at least five energy transfers (steps). The students were allowed to use only the non-electronic parts from their robot kits. However, teams were permitted to add other materials, with the exception of batteries or power supplies. The main intention behind this lab was to provide students with an opportunity to participate in a fun activity while moving through the early stages of team formation. The secondary expectation of this lab was to familiarize the students, particularly the ME team members, with the mechanical parts of the robot kits.

Figure 1: A Rube Goldberg Machine Using Pneumatics and Hydraulics

3.2 Lab Assignment 2: Mobile Bug Behavior

The second assignment was designed to help students learn about the electronic components of their kits as well as give them the chance to practice with the IC4 programming environment. The assignment involved simulating bug behavior (see Figure 2). The goals of this lab were:

- To familiarize students with the Handy Board, various sensors, and different types of motors.
- To have each team design a mechanism for a 1-DoF joint.
- To provide a team experience on an integrated system that includes mechanics, electronics, and computation.

The objective was to build a mobile bug that would "wake up" when exposed to a strong light. The bug was then supposed to scan the area in front of it for the closest object, which it would interpret as a food source. The bug would use the sonar sensor placed on a turret mechanism to accomplish this task. The turret would turn by means of a servo motor. Once the bug identified the closest object, it would be expected to move in the direction of the object. Depending on how the bug determined the direction of the object, this action could have required rescanning. Using touch sensors as "antennae", the bug would find the food and stop to "feed". Human intervention would then remove the food source, whereupon the bug would proceed to search for a new food source. This lab was assigned immediately after the class was given an introduction to the Handy Board, the Interactive C development environment, and the sensors and motors. It was the first lab assignment that incorporated a component of all three disciplines.

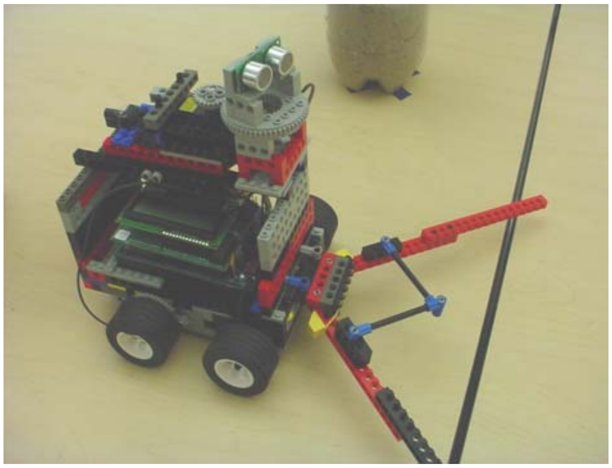

Figure 2: A Bug with Sonar Sensor

3.3 Lab Assignment 3: Homing Light Sensor

The third assignment concerned sensor electronics. It required the design and fabrication of a custom light sensor for use with the Handy Board that could "home in" on a light source (see Figure 3). The goals of the lab were:

- To familiarize the students with interfacing sensors to the Handy Board.
- To have each team design, build, and test a custom electronic circuit able to locate a light source.
- To provide additional integrated system experience in mechanics, electronics, and computation.

The goal area was defined as the set of all points in the working plane within six inches of the light source. The robot's initial position and orientation with respect to the source would be unknown, but was about 24 inches away, and the initial heading would diverge by no more than approximately 45 degrees from the optimal path to the source. The light source consisted of a small light bulb located in the center of the circle and elevated above the surface at a height of approximately six inches. Initially, the light source was turned off and remained off for a minimum of fifteen seconds. The robot was required to remain "quiet" until the light source was activated, whereupon the robot was expected to "home in" on the source as quickly as possible.

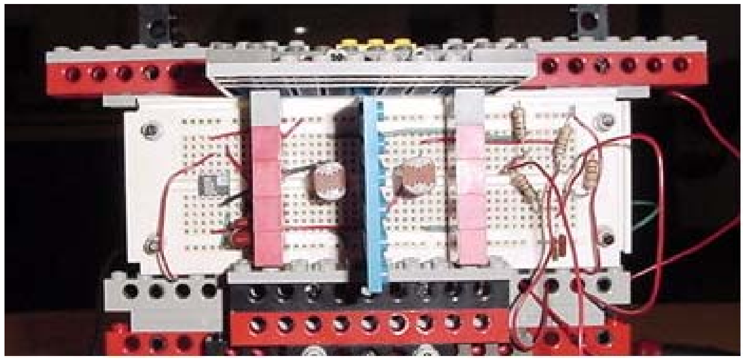

Figure 3: Student Implementation of a Custom Light Sensor

Teams were provided with a printed circuit board (PCB) and parts. The circuit is illustrated in Figure 4. The resistors R_{P1} and R_{P2} represent the resistance of two photocells (left and right eyes). Teams were also given the PCB layout file and C-routines to help them collect test and calibration data. While not required, the teams were encouraged to test their designs by simulation using PSPICE.

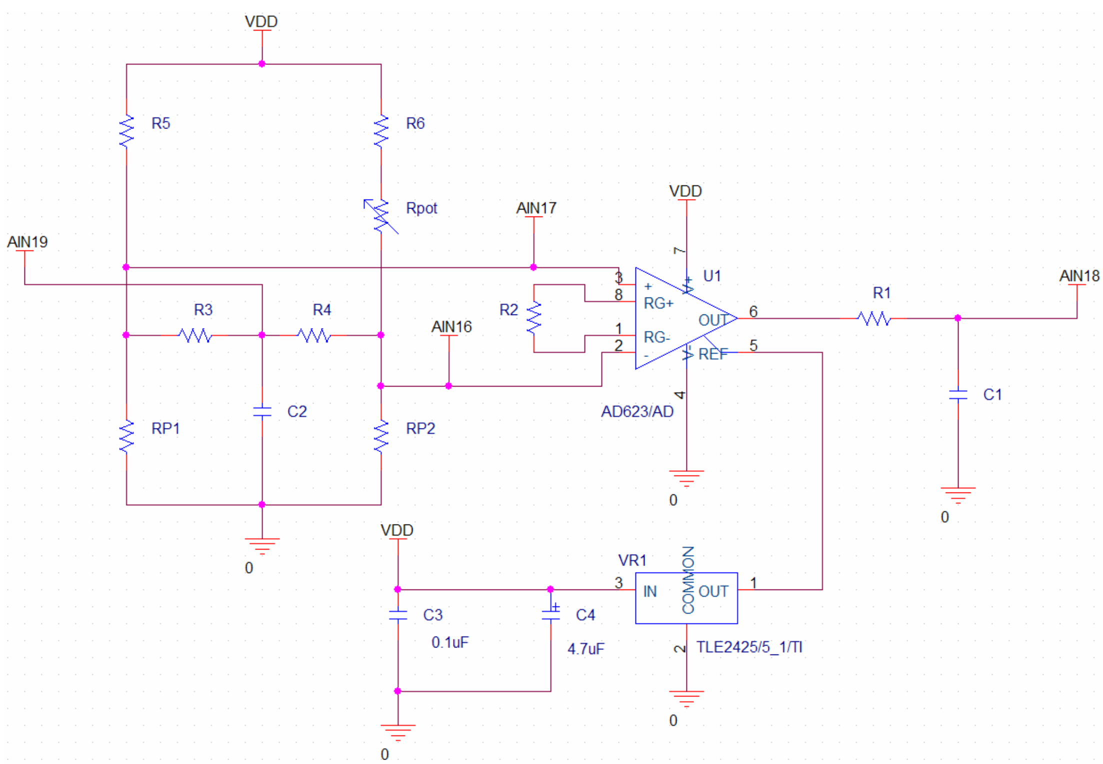

Figure 4: Custom Light Sensor Circuit

3.4 Lab Assignment 4: Robotic Arm

The fourth assignment involved the design of a two-link robotic arm that would accurately track a one-inch-radius circular closed path with its tip (see Figure 5). The center of the circle was located at world coordinates (0, 6) and the tip motion was required to quickly trace out the circle in a counter-clockwise direction, starting and ending at coordinates (1, 6). The link lengths of the arm were six and twenty-five inches. These parameters would lead to two inverse kinematics solutions to the given task. The implementation of a Derivative Proportional (DP) closed-loop control was required to achieve the desired accuracy. In addition, two 25 Ω rotational potentiometers were required to be used to sense the joint angles.

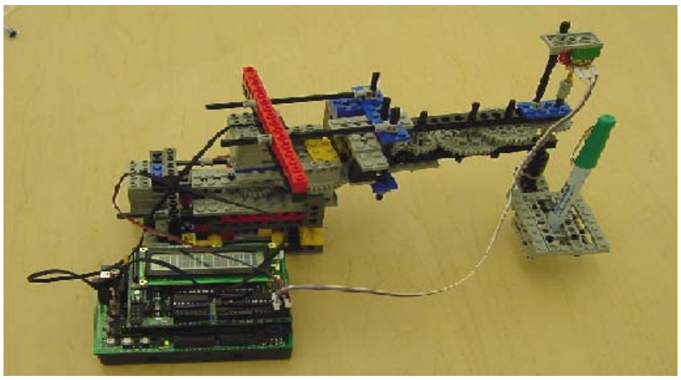

Figure 5: A Two-Link Robotic Arm

3.5 Culminating Project: Autonomous Urban Search & Rescue Robot

The objective of the project was to design and implement an autonomous search and rescue robot for an earthquake-damaged building, using the back story detailed in Figure 6.

> **An earthquake registering 7.5 on the Richter scale along the New Madrid Fault has caused extensive damage across Missouri, Southern Illinois, and Tennessee. An emergency response team was sent out to search for potential victims in a warehouse near I-255, which has suffered severe damage in part of its storage facility.**
>
> **In the midst of their heroic efforts to find and save factory workers, an aftershock measuring a 5.3 on the Richter scale hits and 7 emergency workers, scattered throughout the factory, are too badly injured to escape. Rescue workers have asked that your Robotic Rescue Team dispatch a robot to help identify where the workers are trapped so that critical resources can be focused on the rescue of the emergency workers.**
>
> **The local rescue workers have provided you information about the warehouse that you might find useful for your robot. They have provided a blueprint of the area needed to be searched as well as photos of the facility prior to the earthquake. Your team has been given 25 minutes to search the facility for the rescue workers.**

Figure 6: The Urban Search & Rescue Back Story

The goals of the project were:

- To have each team design and implement an autonomous search and rescue robot.
- To have each team design and implement a custom sensor for sound localization.
- To have each team explore methods of localization.
- To have each team design and implement an algorithm for autonomous navigation.

The search area was a 10’x10’ arena with various obstacles, divided into five rooms with a sixth room located in an upper level that was only accessible by means of a ramp with a 30-degree grade. The robot’s mission was to locate all victims wearing uniforms of a specific color, as well as a victim that was “screaming for help”. The screaming victim was a sound source generating a 2 kHz tone. Another sound source generating a low tone at 200 Hz was also placed in the arena as a “non-victim” sound to determine whether the sensor design was accurately distinguishing the victim sound source. When a victim was detected, the robot was supposed to approach the victim, set off a series of beeps, and record the exact location of the victim in a two-dimensional array. The array, representing a floor map, was downloaded after the robot’s run to check for accuracy.

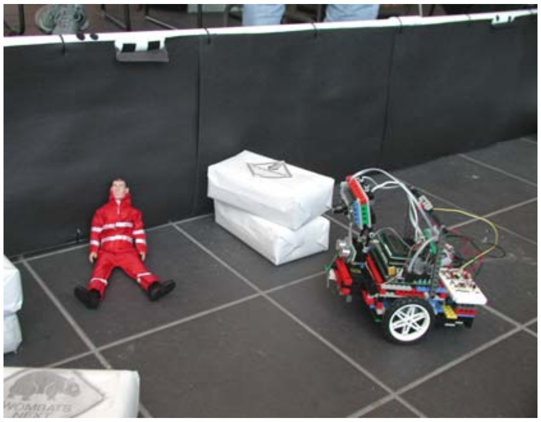

Figure 7: An Urban Search & Rescue Robot Finding a Victim

Project Evaluation

The team’s evaluation of the project was based upon the extent to which a robot visited rooms and discovered victims.

- Each unique room visited: 5 points (maximum of 25 points possible)

    - A robot was required to be entirely inside the room to consider that room visited.
- Each unique victim identified: 4 points (maximum of 28 points possible)
    - A robot's camera was required to be pointing in the direction of the victim (or the sound sensor, if dealing with the "screaming" victim) and be approximately one foot away from the victim when sounding its found signal.
- Indicating a victim on a map within one square foot of actual placement: 3 points (maximum of 21 points possible)
- False identification of a victim could hamper the human rescue workers' effort or put them at unnecessary risk. For each false identification after the first three: 3-point penalty.
    - False identification included pointing in a direction in which there was no victim or identifying the existence of a victim outside of a one-foot radius.
- Lab Report & Post-Mortem Write-Up: 25 points
- Team Meeting Minutes: 10 points

The project was graded out of 100 points, but the evaluation scale permitted the possibility of exceeding 100 points in order to ensure that teams could do well even if they did not accomplish a search of every room and the location of every victim. In a challenging project such as this, with so many real-world variables to overcome and control, if a robot found three to four out of seven victims, it would be considered successful. In addition, to help promote progress being made in each discipline, extra credit was given if the teams demonstrated such aspects in isolation. The specific aspects that were tested were:

- The successful implementation of feedback control to improve the robot's accuracy for going in a straight line: 5 points. This had to be demonstrated by having the robot traverse a three-foot line.
- The successful implementation of feedback control to improve the robot's accuracy and reliability for making a 90-degree turn: 5 points.
- The successful implementation of the sound localization sensor. This had to be demonstrated in the same way that the light sensor was demonstrated in Lab Assignment 3: 5 points.

4. ASSESSMENT AND EVALUATION

In addition to the four course instructors, a fifth faculty member was designated to conduct activities designed to assess the success of the course in meeting its goals with respect to multidisciplinary teamwork. The assessor attended the lectures and project presentations, and oversaw the implementation of numerous assessment tools that were designed to gauge the effectiveness of various aspects of the course. The principal assessment tools are listed below in the order in which they were administered.

1. Pre-Course Survey • This survey was used to gauge the background of the students in CS, ECE, IME, and ME, as well as to help determine team membership. • The students were asked to specify their majors, their course background in the three disciplines (CS, ECE, and ME), their experience with teamwork, and the times that they would be available for team meetings. • Students were asked basic questions from each discipline, that majors should already know, to determine the extent of non-majors' comprehension. These technical questions would reappear on the Final Exam to gauge the effectiveness of the cross-disciplinary instruction.
2. Term Quizzes • Each Term Quiz was designed to contain some questions that were specifically designed to measure the understanding of non-majors (i.e., questions that students within the discipline would be expected to know prior to the course, but that students outside the discipline would not be expected to know prior to the course).
3. Mid-Point Questionnaire • Approximately halfway through the course the students were given a non-technical questionnaire with bulleted questions and essay questions regarding their opinions regarding the course's cross-disciplinary effectiveness.
4. Discipline-Specific Discussion Sessions • About two-thirds of the way through the course, informal sessions with the assessor were scheduled, in which students in each of the CS, ECE, and ME disciplines discussed their concerns about the course and the cross-disciplinary problems they were encountering (if any). These interview sessions included discussions about team efforts up to that point in the course.
5. Peer Reviews of Cross-Disciplinary Teams • Just prior to the final project presentations, students filled out peer review forms for their teammates, emphasizing the effectiveness of the cross-disciplinary aspects of the course's preparation, the effectiveness of their teammates at representing their respective disciplines, and their effectiveness at representing their own discipline within their teams.
6. Project Final Reports • At the end of the semester, each team submitted a final report regarding the project, including a "post-mortem" of what went wrong and what went right. This report included significant feedback on the effectiveness of the multidisciplinary teamwork, as well as suggestions for how this aspect of the course might be improved.
7. Post-Presentation Interviews of Cross-Disciplinary Teams • Within a few days of each team's project presentation at the end of the course, the team met with the assessor to review the cross-disciplinary aspects of the project and the course as a whole.
8. Final Exam • The Final Exam contained several of the technical questions that appeared on the initial Pre-Course Survey, which were used to contrast non-majors' understanding of other disciplines before and after the course. • Additional questions were included on the Final Exam that required the students to make connections between two or more of the course disciplines.
9. Course Evaluations • Additional bubble questions were added to the school's standard Course Evaluation Forms to query the students regarding the effectiveness of the multidisciplinary aspects of the course. Students were also encouraged to provide constructive criticism on the form's essay questions concerning the course.

Table 3: Cross-Disciplinary Assessment Tools

An analysis of the results of these assessment tools provides some insight into the degree to which the course succeeded in its goals of multidisciplinary teamwork and cross-functional learning. These insights are summarized in the following subsections.

4.1 Assessment of Multidisciplinary Teamwork

The Peer Reviews (Mechanism #5 from the list) and the Team Interviews (Mechanism #7) were specifically designed to facilitate the assessment of the extent to which the course successfully provided students with effective experiences within multidisciplinary teams.

Peer Reviews

On the Peer Reviews, students were asked to use a four-point scale to evaluate their teammates with respect to four desired attributes: commitment, cooperation, motivation, and participation. The cross-disciplinary results are displayed in the tables below. Note that no team had more than one CS student but a couple of teams had 2 ECE or 2 ME students.

	Commitment	Evaluated Teammate		
		CS	ECE	ME
Evaluator	CS	NA	3.0	3.1
	ECE	3.3	3.0	2.7
	ME	3.5	3.3	4.0

	Cooperation	Evaluated Teammate		
		CS	ECE	ME
Evaluator	CS	NA	3.3	2.8
	ECE	3.0	3.0	2.8
	ME	3.6	3.2	4.0

	Motivation	Evaluated Teammate		
		CS	ECE	ME
Evaluator	CS	NA	3.0	3.1
	ECE	3.0	3.0	2.5
	ME	3.4	3.3	4.0

	Participation	Evaluated Teammate		
		CS	ECE	ME
Evaluator	CS	NA	2.6	3.1
	ECE	3.4	3.0	2.6
	ME	3.8	3.3	4.0

4=Extremely High; 3=High; 2=Average; 1=Low; 0=Extremely Low

Table 4: Cross-Disciplinary Peer Evaluation Results

Of particular interest in these numbers are the cross-disciplinary asymmetries, in which students from two disciplines perceive each other as having significantly different levels of certain desired attributes. For instance, while CS and ECE students evaluated each other as comparable in terms of commitment, cooperation, and motivation, the ECE students perceived their CS teammates as substantially more active participants than the CS students perceived the ECE students.

Similarly, CS and ME students considered each other comparable in terms of commitment and motivation, but ME students viewed their CS teammates as having higher levels of cooperation and participation than the CS teammates viewed the ME students.

The widest disparity between disciplines in these peer evaluations was between the ECE and ME students, with the ME students considered slightly less cooperative and substantially less committed, motivated, and participatory.

Written comments on the peer evaluation forms tended to display recognition of the contributions of each discipline. ECE and ME students acknowledged how essential it was to have a CS teammate who could design flexible algorithms, and quickly code and debug their implementation. ME and CS students commented upon the critical contributions that ECE students made to circuit design and sensor modifications. Finally, ME students were recognized by their CS and ECE teammates for bringing specific structural and mechanical knowledge to those projects that particularly needed them (i.e., the robotic arm and search-and-rescue projects).

As expected, personalities and different work ethics frequently affected mutual perceptions in the peer evaluations. Common complaints included apathy, procrastination, closed-mindedness, and chronic unavailability. Such comments were far outnumbered by complimentary remarks, however, emphasizing helpfulness, creativity, organization, experience, and pragmatism.

Team Interviews

Each project team met with the course assessor within a few days of demonstrating its search-and-rescue final project to discuss the course's emphasis upon teamwork, and to suggest improvements that might be made to the projects in future versions of the course. In the presence of the entire team, individual team members tended to downplay personality conflicts and praise each other's efforts on the projects. However, there was a certain consensus that the distribution of labor across the disciplines was not equitable. Many teams voiced the opinion that each project should be easily divisible into equal CS, ECE, and ME components, or, alternatively, that preliminary projects should take turns in focusing on particular disciplines, with the final project composed of three comparable, distinguishable parts.

Most of the other comments from students during these team interviews concentrated upon the relative lack of time allocated to some assigned projects, with particular emphasis placed upon the inadequate amount of time provided to design and implement the final search-and-rescue project. A specific recommendation of several teams was to enhance the quality of the final project by designing the earlier lab assignments to serve as components of the final project.

4.2 Assessment of Cross-Functional Learning

Assessment mechanisms designed to gauge the course's success in imparting cross-functional learning included the Pre-Course Survey (Mechanism #1 from the list), the Term Quizzes (Mechanism #2), the Mid-Point Questionnaire (Mechanism #3), the Discipline-Specific Discussions (Mechanism #4) and the Final Exam (Mechanism #8).

Mid-Point Questionnaire

Conducted halfway through the course, the Mid-Point Questionnaire queried the students regarding their background in their own and their teammates' disciplines, as well as the extent to which they and their teammates were contributing to team understanding of the course projects. The results of this survey are summarized in the tables below.

Background In Each Discipline		Evaluated Discipline		
		CS	ECE	ME
Evaluator	CS	3.5	2.8	1.7
	ECE	2.9	4.0	2.3
	ME	2.3	2.8	3.0

4=Extremely Prepared
3=Reasonably Prepared
2=Insufficiently Prepared
1=Unprepared

Contribution To Team Understanding		Team Member's Discipline		
		CS	ECE	ME
Evaluator	CS	3.3	3.0	2.8
	ECE	3.3	3.2	2.9
	ME	3.8	3.6	3.2

4=Indispensable Contribution
3=Significant Contribution
2=Negligible Contribution
1=Negative Or No Contribution

Table 5: Cross-Disciplinary Mid-Point Questionnaire Results

While students from each discipline expressed confidence in their preparation in their own discipline, CS students felt very unprepared for ME material, while ECE students felt somewhat weak in ME and ME students felt rather weak in CS. These perceived shortcomings were rather effectively addressed, however, with ME students evaluated as contributing significantly to their CS and ECE teammates' understanding of the ME discipline's role in the assignments, and CS students evaluated as contributing tremendously to their ME teammates' understanding of the CS discipline's role in the assignments.

Discipline-Specific Discussions

The course assessor conducted open discussion sessions with the students from each of the three disciplines about two-thirds of the way through the course, concentrating on any cross-disciplinary problems that had been perceived by the students. While all three groups expressed favorable impressions of the course as a whole, a common theme in these discussions was the perception that the CS students were rather overburdened in the projects, while the ME students often had little to contribute. CS students saw themselves as "project closers", who were forced to fix last-minute problems with both the ECE and ME portions of the lab assignments. ECE and ME students agreed that their lack of programming experience made it impossible for them to contribute significantly during the latter stages of the assignments. On the other hand, the overwhelming consensus, even among the ME students, was that the early assignments contained negligible ME components, resulting in the ME students feeling rather useless for most of the course. Most students from each discipline advocated a more equitable distribution of the assignment workload across the three disciplines.

Term Quizzes

Term quizzes were administered in each of the four disciplines involved in the robotics course, and each discipline's quiz contained some questions that were designed to help assess the success of cross-functional instruction in the course. Each discipline's instructor designed some questions in such a manner that students from that discipline (who had completed discipline-specific course prerequisites) were expected to know the associated course material before taking the robotics course, while students from other disciplines were not. The student's performance on these quizzes is in the following table.

While students in a particular discipline unsurprisingly tended to perform better on quiz questions from their own disciplines, it is notable that the gap between the mean performance of students from a particular discipline and the mean score of all of the students in the course was usually quite narrow. Each discipline's quiz contained one question with which another discipline's students had difficulty (i.e., ME students performed 16% below the mean for the CS question on algorithm complexity; CS students performed 20% below the mean for the ECE question on resistors; and ECE students performed 9% below the mean for the ME question on inverse kinematics).

Question Discipline & Topic		CS Students	ECE Students	ME Students	Total
Question Discipline & Topic	CS: Finite-State Machines	83%	71%	64%	71%
	CS: Breadth-First Search	88%	72%	82%	80%
	CS: Algorithm Complexity	68%	76%	46%	62%
	ECE: Resistors	35%	82%	64%	62%
	ECE: Capacitors	88%	98%	96%	94%
	ECE: Inverting Gain Amplifiers	63%	64%	45%	57%
	ECE: Non-Inverting Gain Amplifiers	93%	97%	96%	96%
	IME: Gear Ratios	90%	75%	94%	86%
	ME: Transform Matrices	28%	28%	45%	34%
	ME: Forward Kinematics	69%	85%	66%	73%
	ME: Inverse Kinematics	53%	45%	64%	54%

Table 6: Student Performance on Discipline-Specific Quiz Questions

On the other hand, the ECE numbers provide several unexpected insights. ECE students outperformed CS students on the CS question concerning algorithm complexity and their scores on the ME question on forward kinematics far exceeded those of the ME students. Interestingly, the ECE students performed comparatively poorly on the IME question about gear ratios, in spite of the fact that ECE and ME students are required to take the same IME course, while CS majors have no IME course requirements.

Pre-Course Survey and Final Exam

A primary mechanism for measuring the cross-functional learning that occurred in this course was the administration of an ungraded pre-course survey on the first day of the course and a graded final exam on the last day of the course, containing equivalent questions from the disciplines of CS, ECE, and ME. The pre-course survey, which also contained questions regarding previous courses, experience with teams, and time availability outside of class, was ostensibly administered to assess student background and to help formulate project teams. The students were not informed that the survey's technical questions would also appear on the final exam, and the surveys were not returned to the students.

The nature of the questions from each discipline and the comparative averages from each discipline's students are displayed in the table below.

Question Discipline & Topic	CS Students		ECE Students		ME Students		Total	
	Survey	Exam	Survey	Exam	Survey	Exam	Survey	Exam
CS: Binary Trees	88%	90%	10%	68%	0%	76%	29%	77%
CS: Heuristics	13%	100%	10%	85%	0%	77%	7%	86%
CS: Finite-State Machines	50%	100%	32%	84%	0%	81%	26%	87%
CS: Algorithm Complexity	88%	100%	8%	98%	0%	84%	28%	93%
ECE: Resistance	45%	82%	84%	87%	52%	85%	61%	85%
ECE: Operational Amplifiers	0%	59%	68%	91%	12%	64%	29%	72%
ME: Rigid Bodies	0%	60%	28%	57%	66%	82%	34%	67%
ME: Gear Ratios	75%	71%	40%	60%	80%	76%	64%	69%
ME: Force & Torque	33%	83%	50%	90%	86%	100%	58%	92%

Table 7: Comparison of Pre-Course Survey and Final Exam Results

As expected, on the pre-course survey, students performed reasonably well on questions from their own discipline and they performed somewhat better on those questions on the final exam. (A more substantial improvement was demonstrated by CS students on the questions relating to heuristics and finite-state machines, topics not always covered in the CS prerequisites to the robotics course.)

Cross-functional improvement was much more pronounced, with substantial improvements in ECE and ME scores by non-majors, and vast improvements in CS scores by ECE and ME students. An analysis of the academic backgrounds of the students in this course provides a satisfactory explanation for this disparity. CS and ECE students frequently take calculus and physics courses, in which certain introductory ME topics are introduced. Similarly, CS and ME students usually take beginning circuits courses, in which resistors are commonly studied. However, the introductory programming courses to which most ECE and ME students are limited usually do not cover the more advanced CS topics that were included on the pre-course survey and final exam.

4.3 Assessment of Course and Projects

The Project Final Reports (Mechanism #6 from the list) and the Course Evaluations (Mechanism #9) were designed to provide an overall assessment of the effectiveness of the course, and to solicit suggestions from the students regarding improvements that might be attempted in future versions of the course.

Project Final Reports

Each team of students submitted a final report on its search-and-rescue project, which included a "post-mortem" describing the successful and unsuccessful aspects of the team's project and its collaborative efforts as a whole. Teams commonly cited the lack of time for this project (three weeks at the end of the semester) as the principal difficulty, with several standard obstructions to teamwork (i.e., difficulty in establishing meeting times, diverse levels of engagement, insufficient up-front planning, and personality conflicts) also mentioned.

The post-mortem documents recognized the value of interdisciplinary projects and expressed the gain of mutual respect for each other's disciplines as one of the course's primary benefits. The spirit of cooperation in most teams appeared to be quite high, and the opportunity of gaining experience with "experts" from other fields was frequently specified as one of the main benefits of taking the course.

Course Evaluations

At the conclusion of the course, the students were asked to evaluate the course and the instructors via anonymous questionnaires that included essay questions regarding how the course might be improved. The most common comment from students regarded the perceived imbalance between the workloads of the team members from different disciplines. Students from all three disciplines perceived ME as the area that was least utilized in the projects. Coincidentally, the presented lecture material that was seen as least relevant to the projects was ME, which was considered to be presented in too much depth, both by non-ME students and by ME students.

While several students expressed confusion at the four-instructor approach, by and large, students praised the course for providing hands-on experience with practical projects using teams of contributors from multiple disciplines. Complaints concerning the demands that the course made on the students' time were common, but the majority of the students expressed no regrets about having taken the course, as well as strong positive feelings regarding the benefits of having done so. A number of students from each discipline expressed the opinion that this course provided them with the most practical experience of any course thus far in their college careers.

5. FUTURE WORK AND ENHANCEMENTS

The multidisciplinary robotics design course will be taught again in Spring 2005. The assignments and course material shall be altered to reflect the student feedback and instructor perceptions of what did and did not succeed in the pilot version of the course.

5.1 Lab Assignment Restructuring

A common complaint from students in the pilot version of the robotics course was the perception that the preliminary lab assignments failed to adequately prepare the teams for the culminating search-and-rescue project. Many teams reported having difficulty adjusting to the volume of new skills needed on this final project, including camera operation, sound localization, and navigational mapping. A strong consensus was reached among both students and instructors that a more progressive, modular approach to the lab assignments would be more appropriate in the next version of the course, rather than the discipline-centered assignment approach taken in this first version. A comparison of the two approaches is illustrated below.

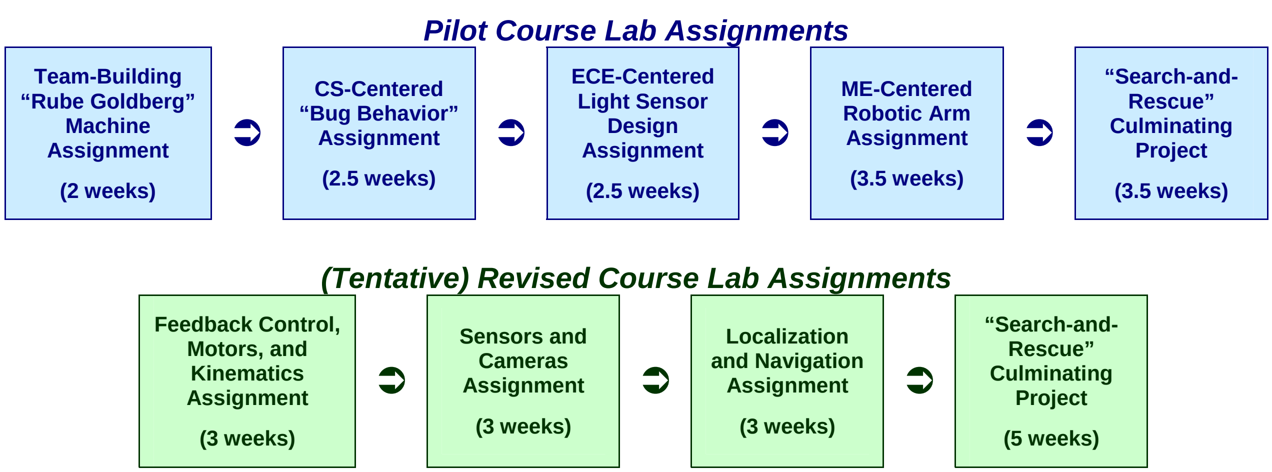

Figure 8: Lab Assignment Progression in Pilot and Revised Versions of the Course

This revision also addresses two other problems with the lab assignments that were cited by students and instructors. First, the pilot version's initial "team-building" assignment was viewed by many as being unnecessary, due to the advanced academic rank of the students and their previous experience with team-oriented projects within their respective disciplines. By changing the initial lab assignment to focus on long-range course goals that should be reasonably accessible early in the term, the process of team-building should be achieved in a more productive manner.

Second, the reduction of lab assignments from five to four should address the commonly voiced problem of inadequate time for the more advanced assignments. In the pilot version of the course, teams were allocated 2 to 3.5 weeks to complete each lab assignment, with only 3.5 weeks allocated to the culminating search-and-rescue project. Under the revised plan, the first three assignments will be allocated three weeks apiece, with five weeks set aside for the culminating project. This will provide teams with adequate time to develop superior designs, as well as to fully test their implementations.

In addition to this anticipated restructuring of the lab assignments, students have expressed a desire for more competitive contests between teams in the course. Demonstrations of the search-and-rescue culminating projects in the pilot version of the course were conducted in a public arena, with dozens of student spectators and extensive local media coverage. This fact proved quite motivating for students, and many indicated that such good-natured competition, even without any impact on grades, provided teams with additional an incentive to excel on the assignments. As a result, the inclusion of head-to-head demos, perhaps with web-posted results, is being considered for the next version of the course.

5.2 Improved Team Management

Perhaps the most counterproductive characteristic of many team efforts in the pilot version of the course was the tendency to "pipeline" the lab assignments, i.e., awaiting the full implementation of prerequisite components of the assignment before proceeding with the design and implementation of later components. This problem usually took the form of CS students failing to construct the software framework for an assigned robotics application until their ECE and ME counterparts completed the implementation of their respective parts of the assignment. This practice often resulted in the last-minute discovery of fundamental design flaws and, consequently, the rushed implementation of only partial functionality.

To encourage teams to better manage their lab assignments, the revised version of this course will require each team to submit an initial design document early in the development process for each assignment (e.g., within the first week of each three- or five-week cycle). These documents will be quickly evaluated, assessing the practicality of the design, the equity of the workload distribution among team members, and the appropriateness of the test plan. With at least half of the allocated time for each assignment still available, it is expected that this practice will alleviate the pipelining problem and improve the overall quality of each team's submitted assignments.

5.3 Reduction in Actively Participating Faculty

The NSF support obtained for this project provided the resources to permit four faculty members to directly participate in course instruction for the pilot version of the course, one each from CS, ECE, IME, and ME. While occasional guest lectures are certainly possible from instructors from each discipline in future incarnations of the course, one of the project's goals has been to produce course materials that would enable a single instructor to effectively teach the course to a multidisciplinary student body.

In the Spring 2005 version of the course, the set of instructors will be reduced from four to two. The CS and IME instructors will continue to be directly involved with course instruction, making use of the course materials (and possible guest appearances) of the ECE and ME instructors. The refinement of the course notes and assignments from this next version are expected to produce a body of instructional materials (including the possibility of a multidisciplinary robotics textbook) that will facilitate this course being conducted by instructors from any one of these disciplines in the near future.

5.4 Dissemination of Course Material

The current course materials for the integrated systems design course in robotics are available on-line at http://roboti.cs.siue.edu/classes/. The second iteration of the course will begin in January 2005. Complete course materials including lectures with instructor notes and assignments with grading rubrics will be in Summer 2005, along with an ensuing report on the course's effectiveness and the insights of teaching multidisciplinary teamwork afforded by the NSF project.

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