Multidisciplinary Teamwork in a Robotics Course

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ABSTRACT

Real-world systems are comprised of interdependent components creating integrated systems. These systems are developed by multidisciplinary teams. The goal of this project is the development of a comprehensive undergraduate course in robotics that encompasses various fields that are integral to robotic systems: Computer Science, Electrical and Computer Engineering, and Mechanical Engineering. A main pedagogical goal of the course is to teach group dynamics and the skills necessary for interaction with people in different disciplines in multidisciplinary teams. Descriptions of the course and the hands-on lab assignments are presented along with 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.

Keywords

Robotics, sensors, manipulators, kinematics, feedback control, localization, navigation, multidisciplinary, cross-functional, teamwork.

1. INTRODUCTION

Real-world complex systems are comprised of an assortment of integrated components from multiple disciplines. The development of such systems has shifted from designing individual components in isolation to working in cross-functional teams that encompass the variety of expertise needed to devise such systems [8,14]. 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 has acknowledged the importance of these abilities in its *Criteria for Accrediting Engineering Programs* [5]. The study of robotics provides an excellent instrument for teaching and learning about working in multidisciplinary teams.

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Robots are complex integrated systems comprised of interdependent electrical, mechanical, and computational components. 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 [1,4,9]. 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), and Mechanical Engineering (ME). 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 material from [4,6,7,10,14,16].

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

- To gain hands-on experience in practical robotics
- To learn about integrated system design
- To learn to interact with people in different disciplines in a cross-functional team
- To learn about group dynamics and teamwork

This paper presents the outcome of the first offering of the course, which was taught by a team of faculty members from all of the represented areas. 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 have the full range of engineering expertise that is represented in such a comprehensive course. Informed by the assessment of the first year the material will be further developed to allow the course to be taught by a single faculty member.

2. COURSE ORGANIZATION

The course, entitled "Robotics: Integrated System Design", was offered for the first time in Spring 2004 as a senior-level elective in the three majors: CS, ECE, and ME. Enrollment limits were used to achieve a balanced enrollment between the majors for the purpose of team formation. Following the guidelines put forth in [4], 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. 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 [13,14,15], 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. The general topics covered were control theory (i.e., kinematics, feedback control), sensors (i.e., circuits and signal processing, computer vision), and artificial intelligence (i.e., localization, planning).

Table 1: Week-by-Week Schedule of Class Topics

Day 1	Day 2
Introduction to Robotics	Teamwork/Group Dynamics
Robot Technical Fundamentals	Forward/Inverse Kinematics
Forward/Inverse Kinematics	Introduction to Handy Board
Feedback Control	Feedback Control
Electronics Primer/Sensor Fundamentals	Circuits
Sensor Operating Principles	Advanced Sensors
ME & ECE Quiz	AI and Reactive Control
Computer Vision/Image Processing	Localization/Navigation
Localization & Navigation	Planning
Problem Analysis/System Design	Final Project Assignment
Multi-Robot Coordination	Multi-Robot Coordination
Time & Space Complexity	Robot Competitions
CS & IME Quiz	Project Troubleshooting
Final Project Presentations	Final Project Presentations
Final Project Demonstrations	Final Project Demonstrations

The topics were ordered using a layered abstraction approach [3], 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 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 exam to ensure that students made a sincere effort to learn concepts from disciplines that were complementary to their own: Team Assignments 25%, Team Project 30%, Quizzes 25%, and Final Exam 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. Although this aspect of the course was not specifically formalized (as suggested in [4]), both single teams and multiple teams were observed studying together 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 [2,4,16]. The specific topics included:

- What defines a team?
- Team process: team roles, decision making, conflict resolution
- 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

During the in-class exercises, the teams were instructed to practice the same team process they were expected to use during their team meetings. This included assigning team roles, setting a meeting agenda, and recording results. The identified team roles were Chief Technology Officer (CTO), Scribe, and Rat Hole Watcher. The CTO is the identified leader of the project, and this role was expected to rotate between team members based on the emphasis of the particular assignment. The Scribe is responsible for recording the results of each team meeting. Team minutes were required to be submitted as part of the grade for each assignment. Finally, the Rat Hole Watcher is empowered to stop a line of conversation that is off topic in order to keep the discussion focused.

The choice of robotics platforms for the team assignments and projects included LEGO mechanical pieces and the Handy Board Controller [11]. This platform was chosen for its mechanical flexibility, its ability to easily interface with custom-built sensors, the availability of a C development environment, and the availability of a low-cost color camera, the CMUcam. 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, and a Handy Board. In addition, electronic parts were purchased for labs that required the development of custom sensors as discussed in Section 3.

3. HANDS-ON LAB ASSIGNMENTS

The overall philosophy of the lab assignments is to provide a hands-on, multidisciplinary design experience that complements the lecture material. 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 [12]. 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 [14].

3.1 Assignment 1: Rube Goldberg Machine

The first assignment involved the design and implementation of a Rube Goldberg Machine (www.rgmc.com) that would capture a mouse without harming it. In addition to familiarizing the students with the building materials in the kit, this assignment was designed to place the students in a frame of mind for designing and building. 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.

3.2 Assignment 2: Mobile Bug Behavior

The second assignment was designed to help students learn about the electronics components of their kits and give them experience with the programming environment. The assignment involved simulating bug behavior. Using the Handy Board, various sensors and motors, and a team-designed 1-DoF joint mechanism, each team would gain experience on an integrated system that included mechanics, electronics, and computation.

The objective was to build a mobile bug that would “wake up” when exposed to a light. Using a sonar sensor on a turret mechanism, the bug was to scan the area in front of it for the closest object, which it would interpret as a food source. Once the bug identified the object, it was expected to move in the direction of the object. Using touch sensors as “antennae”, the bug would find the food and stop to “feed”. If the food source was removed, the bug was to search for a new food source.

3.3 Assignment 3: Homing Light Sensor

The third assignment required the design and fabrication of a custom light sensor that could "home in" on a light source. 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 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.

3.4 Assignment 4: Robotic Arm

The fourth assignment involved the design of a two-link manipulator robotic arm that would accurately track a one-inch-radius circular closed path with its tip. The manipulator parameters would lead to two inverse kinematics solutions to the given task. The implementation of a Proportional Derivative (PD) closed-loop control was required to achieve the desired accuracy. In addition, two rotational potentiometers were required to be used to sense the joint angles.

3.5 Project: Autonomous Search & Rescue

The objective of the culminating project was to design and implement an autonomous urban search and rescue robot for an earthquake-damaged building, as detailed in Figure 1.

The project assignment was designed to have each team explore localization methods (including the design and implementation of a sensor for sound localization), and develop an algorithm for navigation.

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 1: The Urban Search & Rescue Back Story

The search area was a 10’x10’ area 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. The robot’s mission was to locate all victims wearing uniforms of a specific color and one victim that was “screaming for help”. The screaming victim was a sound source generating a 2 kHz tone. When a victim was detected, the robot was to approach the victim, set off a series of beeps, and record the 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.

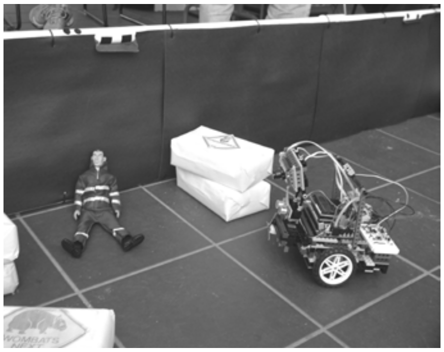

Figure 2: A Robot Finding a Victim

The evaluation of the project was based upon the extent to which a robot visited rooms and discovered victims. 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 certain aspects in isolation:

- The implementation of feedback control to improve the robot’s accuracy for going in a straight line.
- The implementation of feedback control to improve the robot’s accuracy and reliability for making a 90-degree turn.
- The implementation of the sound localization sensor.

4. ASSESSMENT AND EVALUATION

A number of assessment tools were designed to gauge the effectiveness of various aspects of the course. While the other members of the research team were instructors for the course, one member was designated the course assessor, who was responsible for implementing the assessment tools.

4.1 Multidisciplinary Teamwork Assessment

Peer reviews and team interviews were specifically designed to facilitate the assessment of the extent to which the course successfully provided students with effective experiences within multidisciplinary teams.

On the peer reviews, students were asked to evaluate their teammates with respect to four desired attributes: commitment, cooperation, motivation, and participation. 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.

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, particularly 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 Cross-Functional Learning Assessment

Assessment mechanisms designed to gauge the course's success in imparting cross-functional learning included a mid-point questionnaire, discipline-specific discussions, term quizzes, a pre-course survey, and the final exam

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. 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.

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 CS students were rather overburdened in the projects, while ME students often had little to contribute. Most students from each discipline advocated a more equitable distribution of the assignment workload across the disciplines.

Term quizzes were administered in each of the course disciplines, and each quiz contained some questions that were designed to help assess the success of cross-functional instruction in the course. Each discipline's instructor designed questions for which 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. While students 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.

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 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.

As expected, students performed reasonably well on questions from their own discipline on the pre-course survey, and somewhat better on those questions on the final exam. 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. However, the programming courses to which most ECE and ME students are exposed usually do not cover the more advanced CS topics that were included on the pre-course survey and final exam.

5. FUTURE WORK

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 course was the perception that preliminary assignments failed to adequately prepare the teams for the culminating 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.

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 Number of Instructors

While the pilot version of this course had four actively participating instructors, the Spring 2005 version will only have two and, with the refinement of course materials, the expectation is that future incarnations of the course may be taught by a single well-prepared instructor from any of the four disciplines, with the possibility of an occasional guest lecture by an expert from one of the other areas.

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7. REFERENCES

[1] Beer, R., Hillel, C., and Drushel, R. Using Autonomous Robotics to Teach Science and Engineering. *Communications of the ACM 42*, 6, June 1999, 85-92.

[2] Beyer, H. and Holtzblatt, K. *Contextual Design: Defining Customer-Centered Systems*. Morgan Kaufmann, Inc., 1998.

[3] Crabbe, F. Unifying Undergraduate Artificial Intelligence Robotics: Layers of Abstraction Over Two Channels. *2004 AAAI Spring Symposium Technical Report SS-04-01,* AAAI Press, 2-7.

[4] Csernica, J., Hanyak, M., Hyde, D., Shooter, S., Toole, M., and Vigeant, M. *Practical Guide to Teamwork*. June 2002. http://www.departments.bucknell.edu/projectcatalyst/ EngEdWksp2003CD/

[5] Engineering Accreditation Commission (Accreditation Board for Engineering and Technology, Inc.). *2001-2002 Criteria for Accrediting Engineering Programs.* December 2000. http://www.abet.org/images/ eac_criteria_b.pdf/.

[6] Greenwald, L. Tools for Effective Low-Cost Robotics. In *Working Papers of the Spring 2001 American Association of Artificial Intelligence Spring Symposium*; Session on Robotics & Education, March 2001.

[7] Greenwald, L, and Kopena, J. Mobile Robot Labs. *IEEE Robotics and Automation 10*, 2, June 2003, 25-32.

[8] Hartfield, B. The Designer's Stance. In *Bringing Design to Software*. T. Winograd, ed., Addison-Wesley, 1996.

[9] Klassner, F. A Case Study of LEGO Mindstorms Suitability for Artificial Intelligence and Robotics Courses at the College Level. In *Proceeding of the 33rd SIGCSE Technical Symposium on Computer Science Education* (Northern Kentucky), February 2002, 8-12.

[10] Kumar, D. and Meeden, L. A Robot Laboratory for Teaching Artificial Intelligence. In *Proceedings of the Twenty-Ninth SIGCSE Technical Symposium on Computer Science Education* (Atlanta), 1998, 341-344.

[11] Martin, F. *Robotic Exploration: A Hands-On Introduction to Engineering*. Prentice-Hall, Inc., 2001.

[12] Miller, G., Church, R., and Trexler, M. Teaching Diverse Learners Using Robotics. In *Robots for Kids: Exploring New Technologies for Learning.* A. Druin and J. Hendler, eds., Morgan Kaufmann, 2000, 165-192.

[13] Pinto, M.B., and Pinto, J.K. Project Team Communication and Cross-Functional Cooperation in New Program Development. *Journal of Product Innovation Management 7*, 1990, 200-212.

[14] Rosenblatt, M. and Choset, H. Designing and Implementing Hands-on Robotics Labs. *IEEE Intelligent Systems 15*, 6, November/December 2000, 32-39.

[15] Song, X.M., Montoya-Weiss, M.M., and Schmidt, J.B. Antecedents and Consequences of Cross-Functional Cooperation: A Comparison of R&D, Manufacturing, and Marketing Perspectives. *Journal of Product Innovation Management 14*, 1997, 35-47.

[16] Weinberg, J. B. and Stephen, M. A Laboratory Experience for Teaching Participatory Design in a Human-Computer Interaction Course. In *Proceedings of the 2002 ASEE Annual Conference & Exposition* (Montreal), June 2002.