AC 2010-22: MOBILE ROBOTICS: A TOOL FOR APPLICATION-BASED INTEGRATION OF MULTIDISCIPLINARY UNDERGRADUATE CONCEPTS AND RESEARCH

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"Mobile Robotics: A tool for application-based integration of multidisciplinary undergraduate concepts and research"

Abstract

This paper presents the development of a mobile robotics course at the primarily undergraduate engineering school, Rose-Hulman Institute of Technology. This course is one of the final courses in the multidisciplinary educational robotics certificate program. The purpose of this course is to use the robot to provide the students with an appreciation of their discipline and how it applies to other disciplines. It is hypothesized that students will gain a more realistic model of their future workplace demographic while also learning about robotics theory and the open areas of robotics research.

Introduction

Undergraduate students in science and engineering frequently express a desire to relate the abstract theory presented in class to real-world or practical application. One method that can be used to integrate component theory with system or practical application is robotics. Since robotics theory includes topics such as sensors, controls, mechatronics, kinematics, microcontroller programming, embedded systems and software development; it is an ideal model for multidisciplinary application. Students from several disciplines including electrical and computer engineering, computer science and software engineering and mechanical engineering can work together in a robotics course to gain depth understanding of their major and breadth understanding of another major. It is hypothesized that this type of classroom experience is a more realistic simulation of their future workplace.

Robotics is typically used as an artifact to engage K-12 students in science, technology, engineering and mathematics (STEM), recruit students to STEM, teach concepts such as programming, controls or embedded systems and also to teach freshman or senior design. Based upon mainstream media, movies, film and K-12 competitions; students gain interest in robotics but also at times an unrealistic perception of the state of the art. Typically, undergraduate robotics courses suffer from lack of a good textbook and either too basic or too complicated activities because of student pre-requisite knowledge and skill.

This paper will present the details of the development and offering of an upper level course ("Introduction to Mobile Robotics (IMR)") designed to teach multidisciplinary robot theory and application that also gives the students an appreciation for some of the open research issues and challenges. The Introduction to Mobile Robotics course is one of the last courses in the multi disciplinary robotics certificate program at the Rose-Hulman, so some students have prior experience with robotics (http://robotics.rose-hulman.edu). This course is innovative in the fact that it is available to students from multiple disciplines and attempts to motivate students for further study or research in robotics versus using the robot as a tool to motivate some other topic. This is compelling because these students are already interested in STEM fields and have or will take courses in design, software, programming, electronics, controls and kinematics. Since this course is taught at a primarily undergraduate engineering institution it is of particular importance that the course also serves as a recruiting tool for undergraduate or graduate research as well.

This course will provide the student with a synthesis and evaluation of engineering and science concepts learned in prior courses. It will not only include mobile robot theory but the implementation of behaviors and control algorithms on an actual mobile robot. Students will gain exposure to the theory but also some of the challenges that face roboticists such as sensor and odometry error and bandwidth limitations. Finally, students will learn about a topic that interests them, engages them in multidisciplinary work, corrects some common robotics misconceptions and potentially recruits students for research.

Literature Review

The goals of this special topics course in mobile robotics are to teach students about robotics history, theory and research while they also gain an appreciation for multidisciplinary work. One of the first steps in the design of the course was to review the literature and identify other courses with similar goals and objectives. This search produced many robotics related courses but surprisingly few with the objective of teaching robotics. In other words, it was difficult to find courses that were using robots to teach robotics (i.e. robots for robotics sake). The diversity of courses found provided more evidence that it is indeed an ideal multidisciplinary tool for teaching concepts in science and engineering. Some of the courses were at the pre-college level and robots were used to increase or maintain students' interest in science and mathematics[1 -5]. These courses typically used LEGOS, RugWarrior and a Handy Board microcontroller. Some of these courses and activities were to prepare students for competitions such as FIRST and Botball, which have proven successful for recruiting students to science and engineering.

At the collegiate level, there were courses for underclassmen to introduce them to programming, computer science and engineering concepts[6 - 17]. The vast majority of these courses were in computer science, electrical, computer and mechanical engineering departments. These courses were overwhelmingly single discipline with only a few cross listed in multiple departments. There were also several courses that used robots to teach microprocessors, microcontrollers, and embedded systems concepts[18 - 23]. Robotics has also been used to provide students with a multidisciplinary team experience as they learn the engineering design process[24 -41]. In most of these courses, the students would design and build a LEGO robot to accomplish a given task. The controller for these courses was typically the Basic Stamp or Handy Board controller. Furthermore, some of the authors even surmised that robot design can be used to satisfy ABET core outcomes a – k as well[29 - 31]. Table 1 presents a summary of related courses that had components similar to the mission of the IMR course. It should be noted that many of these courses were discipline-specific and may have used the robot to motivate another topic as well.

Table 1: Summary of Related Courses

School	Content Summary	Hardware
Brown University	Embodied Gaming	Roomba[42]
Drexel University	CS, AI, engineering problems	LEGOS w/HandyBoard[43]
University of West Florida	Curriculum integration	LEGOS w/HandyBoard[44]

Swarthmore College	Research project preparation, AAAI	Khepera, ActivMedia Pioneers[45]
Missouri University of Science and Technology	State of the art of robotics and architectures	Instructor-created kit using embedded C, Matlab image processing[46]
Carnegie Mellon University	Robots for study problem-based laboratory experiments	LEGOS with HandyBoard[47-48]
Pontificia Universidad Catolica de Chile	mobile robot programming for autonomous navigation	ER1 Mobile Robot[49]
Augsburg College	CS course on robot history and theory	Robix Manipulator, instructor-created vehicle[50]

Course Format

The first offering of the IMR course was in spring 2007 and it quickly became apparent that the proposed topics were too ambitious. The topics included simulation, actuators, effectors, locomotion, kinematics, sensors, control, navigation, localization, path planning, computer vision, image processing, human-robot interaction and GUI design. The problem was that some of these topics were entire courses in themselves (i.e. computer vision, human-robot interaction). Although it was preferable to prepare students for robotics research after one quarter, it was soon discovered that it was just not feasible after a one quarter course. For the second offering of the course in spring 2009, this list of topics was greatly pared down and the result was that the course was more effective. If this course continues to be successful then the eliminated topics will included in a subsequent course or alternate course.

The grading scale was also changed to put more weight on the final project, laboratory assignments and daily reading quizzes. This was because with the amount of programming required to implement AI techniques on the robot, it was not possible to also assign a significant amount of homework or exams. This change was to encourage the students to do the required reading and review the concepts presented in class daily. Robotics is a topic that requires a continuous focus versus intermittent review. This model did appear to work better for getting the students engaged in the material and not just the robot. Furthermore, there were less late submissions of the laboratory assignments and the quiz grades were relatively high. One additional change for the next offering will be that the quizzes will be closed book and notes with a stricter time limit. In the past, it appeared that some students did not prepare for the quizzes but rather used their time during the quiz to search through their notes and textbook for answers. This may have resulted in the high quiz grades and unusually long time to complete the quizzes. The quizzes were designed to be completed in 5 to 10 minutes and it sometimes took the students in excess of 30 minutes. It was also observed during the first course that it was necessary to correct student misconceptions that the course was only about "playing" with the robot. The author believes that students with a sincere interest in the subject matter (not just the robot) should be able to answer basic robotics history and theory questions.

Originally before the robotics certificate curriculum, this course had no prerequisites other than junior level classification and programming proficiency. It was open to the following majors: Computer Science, Computer, Electrical, and Mechanical Engineering. It was soon discovered that students overestimate their programming ability and having lax prerequisite requirements allowed students to enroll who were not prepared for the level of rigor of this course. Thus, in the subsequent course, the prerequisites were changed to control systems and programming proficiency or instructor permission. This change served as a filter for the course to allow upper level students and those who were serious about the subject matter to enroll. The students' major was not a consideration as much as their ability to meet those requirements. It was believed that the student could learn any of the basic electronics or mechanics, if the desire was there. For example, since Computer Science students do not typically take controls, this supplemental instruction could be provided if necessary. Instructor permission to waive the prerequisite requirements was reserved for students enrolled in the robotics certificate curriculum or who have prior exposure to robotics (i.e. FIRST). In this way, the success of this course and the students' success in this course were not so closely tied to their unrealistic expectations of what they could do with a robot and what a robot could do. This was the lesson learned after the first offering of the course when the students really struggled to program the robot and complete the labs.

Originally the course was offered 4 days a week with 3 days of one-hour lecture and one 3-hour lab period. The lab session was for last minute code revisions and robot demonstration. After the first offering, it was determined the students needed more in class time with the robot. Even though the students were allowed to check the robot out and take it home, they were rarely able to meet the lab assignment submission deadlines. This shortfall could be attributed to two factors: instructor and student inexperience. Since this was the first offering of the course, the instructor overestimated the students' programming abilities and the lab expectations were too difficult. Secondly, the students overestimated their abilities and did not log the required 8 hours per week working with the robot outside of class. Therefore, in the second offering of the course, the format was changed to 3 days per week, two hours per day. The first two days included one hour of lecture and one hour of lab recitation or lab work. The last day of the week was for lab completion and demonstration. This allowed the students to work with the robot for at least an hour every day. This change gave the students more opportunities to ask questions and gauge whether their progress was reasonable by observing their peers. This resulted in more of the students completing the laboratory assignments in a timely manner. However, it did reduce the amount of lecture time and put more responsibility on the students for independent study and reading. Despite this, it appeared that the students were able to obtain a more depth understanding of the required robot theory and application and a greater since of accomplishment with the robot. The last two weeks of the course did not include lecture because the students used that time to prepare for the final project and demonstrate robot milestone tasks.

Lectures

This course will be offered for the third time in spring 2010 and each time it has been taught with a different textbook, lectures and labs. Since this textbook is the template for the course, it is important to select one that is appropriately detailed with relevant coverage. However, it is very difficult to find a textbook for an undergraduate multidisciplinary mobile robotics course that is not too advanced or too basic for the objectives of the course. Some textbooks overly simplified key robotics concepts and focused primarily on depth coverage of hardware, typically LEGOs. Other textbooks presented depth coverage of higher-level concepts in controls and probability and neglected the presentation of basic applications. Still, there were other textbooks that were very fundamental or introductory and did not provide enough detail to implement the techniques on an actual hardware platform. This divergence in presentation created great difficulty in the ability of the student's to master the material and apply it to the physical robot. One solution to this problem was to provide more in-class lectures regarding the implementation on the mobile robot. Similar to what other courses have done, the IMR course is slowly moving toward no formal textbook in lieu of handouts, research papers, web resources or a course packet. In order to present the higher level topics in AI robotics, some of the lower level topics such as effectors, actuators, locomotion, and sensors will have to be sacrificed or introduced in a just in time lecture. It is believed that this modification will get the student prepared to complete the laboratory assignments and final project quicker. Based upon several student requests, some brief lectures on the Visual C# IDE and programming concepts such as threading will also be added during the first weeks' lecture. The lecture format was typically a multimedia presentation with PowerPoint, images, videos and some active learning activities such as partial lecture notes, collaborative think-pair-share and paired programming or coding.

Hardware

One of the biggest dilemmas in the design of this course was the selection of the robot platform. As previously mentioned, although the LEGO Mindstorm was a very popular choice, the author felt that the students needed a different platform that was less simplistic and capable of a more diverse sensory suite. Since many students have been exposed to LEGOS in K-12 or other undergraduate courses, the reasoning was that they may not view this platform at the desired higher level required to treat it as a tool for traditional robotics research and application. This platform actually occludes some of the hardware and programming dilemmas that the student should experience in order to appreciate the state of the art. For similar reasons, the Creates (Roombas) using Python, which are used in the introductory programming course at Rose-Hulman were also not selected.

In 2007, the hardware platform was a Traxster I robot programmed using a MicroChip PIC 18 microcontroller. Using this hardware and concepts presented in class, the students were able to implement wall following, obstacle avoidance, follow center, and follow robot behaviors on the mobile robot. In order to implement these behaviors, the students integrated concepts from courses in controls, mechatronics, communications, microcontrollers, and programming. The students programmed the mobile robot using feedback and reactive control. In 2009, the controller on the robot was changed to a Robotics Connection Serializer. The robot was upgraded to a Traxster II with different motors with quadrature encoders. The tracks were removed from the differential drive Traxster and replaced with LEGO kit wheels and a caster due to numerous problems with slippage, the skid turn and severe inaccuracies in odometry. The new robot included a greater diversity of sensors in order to create flexibility and solutions in the laboratory assignments. Table 2 presents the robot sensors and peripherals.

Table 2: Robot sensors and peripherals

- Buzzer
- Camera
- Compass
- Infrared Sensor
- Keypad
- LCD Display
- Line Following Sensor
- Pushbutton I/O Board
- Sonar Sensor
- Thermopile Array
- Text to Speech Synthesizer

Software

The PIC 18 microcontroller for the original offering of the course was programmed in PICCLITE using MPLAB. Although the students were able to accomplish a lot, some of them expressed a desire to use Bluetooth communication and Microsoft Robotics Studio (MSRS) as an option. The reason was that programming at the bit level could be cumbersome and it took the students a long time to set hardware configurations, timers, interrupts, etc. There was a significant amount of code and hardware preparation just to get the robot going. Therefore in 2009, the controller was changed to the Robotics Connection Serializer that could be programmed with Visual C# using MSRS services[54, 55]. This format was actually more appropriate because it moved the focus from components to higher level functions and behaviors. The object oriented programming in an IDE afforded the creation of a GUI to make it possible to visualize the framework of the student's work. By changing to this software platform, students were able to accomplish more basic robot behaviors quicker because they were not bogged down in setting bits as opposed to using a simple function call. These functions were used to control actuators and poll sensors. It should be noted that in both instances of the course, the students were given starter code but even with this assistance there was a significant difference in their performance between the two classes. Even in the new format, some students did not want to use the PID motor controller available in the Serializer library but rather desired access to the hardware such as encoder counts, event and timer interrupts in order to create their own motor controllers and sensor functions. There are always tradeoffs in the selection of any hardware and software platform but despite these, the author feels that using the higher level language was more beneficial for the study of robotics theory and more appropriate for the goals of this course.

Labs

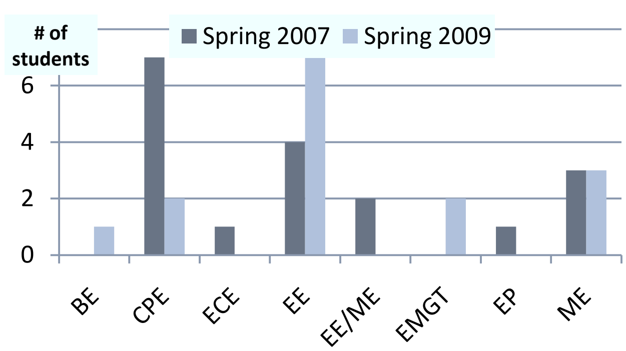
The inspiration for the laboratory assignments was the course topics, other robotics courses, and the three textbooks [51, 52, 53]. The purpose of the laboratory assignments was to expose the students to robot applications founded in the essential theory. This included the implementation of basic robot behaviors such as wall following, obstacle avoidance and navigation to achieve prescribed tasks. During these challenges, the students also encountered some challenges in robotics research such as odometry error, sensor noise and bandwidth limitations. Although, the students may not have always been able to resolve these issues, it is hoped that the experience caused them to think about the field of robotics from a more realistic perspective.

Final Project

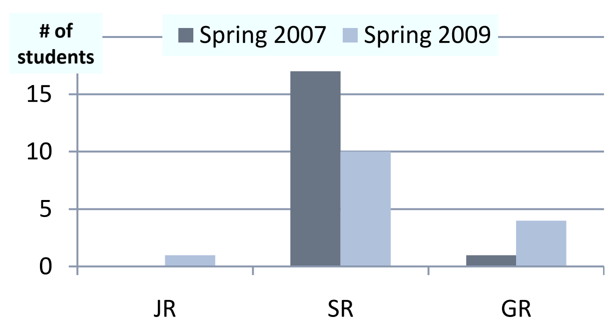
The final project for spring 2007 was a competition similar to a relay race. This project combined several of the robot behaviors implemented during the quarter. As part of the competition, students used wall following, follow center of the hallway, object following and obstacle avoidance to move the robot to a goal point. The students overall score was based upon time and bonus points were awarded for the high scorers. The final project for spring 2009 was a navigation task where students used metric path planning to move the robot from a start to a goal point for several worlds. The students score was based upon accuracy and time and the high scorers received bonus points. More details regarding the final project will be provided in the results section of the paper and on the course website.

Results

This section will present the results of two offerings of the IMR course. Due to hardware limitations, the enrollment in the course was limited to 18 and 15 students, respectively. It should be noted that a typical class size at Rose-Hulman is 20 to 30 students. The reason for the strict limitation on the enrollment was based upon the lesson learned from the first offering. Ideally, there should be enough spare robots for 50% of the class. Unfortunately, there is no simulator available for the Traxster robot so by using this rule, the students continue to make progress on their laboratory assignments while their primary robot was repaired. Typically, the hardware failures were with Bluetooth modules, Serializer boards, track links, and wiring problems. Since there are 10 robots available for the course, the enrollment was limited to 14 students separated into teams of two. Figure 1 provides the course demographics for the two offerings of the IMR course. It should be noted that since the robotics certificate program is only in its second year, it is believed that the diversity of majors, classifications will continue to improve. So far, only 3 students have graduated from the robotics certificate program and they completed the IMR course in spring 2009. These students were able to complete the certificate requirements because they had designed custom made programs to take all robotics related courses in ECE, ME and CS before the inception of the formal program curriculum. The robotics certificate faculty is also researching the possibility of opening up the robotics minor to biomedical engineering students which would also significantly increase the number of female students who enroll in the course. In the two offerings, there have only been 3 women.



a. Student Majors

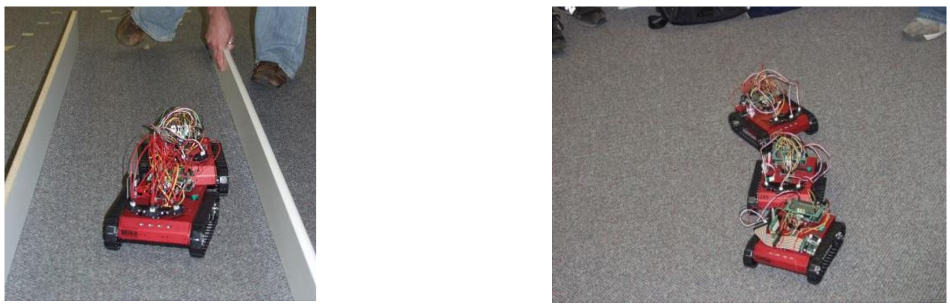


b. Student Classifications

Figure 1: Course Demographics

Labs

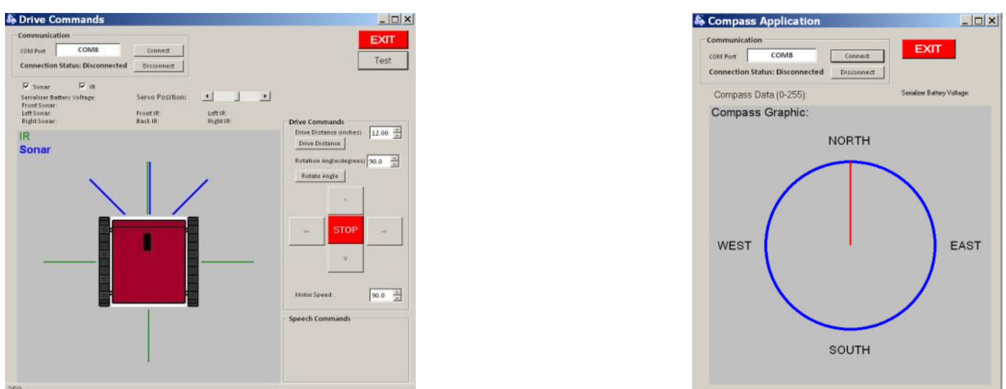
In spring 2007, one of the more successful lab experiments was the implementation of follow center, follow object and follow robot behaviors on the Traxster I. The robot had 4 infrared sensors mounted on the chassis and 3 mounted on the servo. Reactive control was used to program the robots to follow a given trajectory until it encountered objects on both sides (i.e. a hallway). The robot would then adjust its trajectory to drive forward down the center of the hallway. For the follow object or follow robot behavior, the robot attempted to follow an object in the front while maintaining a distance of 5 inches. While following the object, if another object appeared closer, the robot abandoned the first object and attempt to follow the new one. The students were required to create the pseudo code, flowchart and then demonstrate the final design on the physical robot. Figure 2 demonstrates Follow Center and Follow Robot behaviors. As part of each week's lab report, the student was to reflect on the essential theory, challenges encountered, how to address these challenges and how to improve the robot's behavior and/or laboratory assignment.



a. Follow Center b. Follow Robot

Figure 2: Sample Robot Behaviors

In spring 2009, the students were provided with starter Visual C# code for motor and servo control and polling sensor data from the Serializer including the IR sensors, sonar, thermopile array, compass, line following sensor and pushbuttons. The starter code was provided in the form of a GUI with the underlying code. Figure 3 presents a sample of two of the GUIS that the students were given.



a. IR, Sonar, Drive App b. Compass App

Figure 3: Visual C# GUI Screen shots

In one of the first labs of the quarter, the students implement a wall following behavior on the robot using open loop control. In the subsequent lab, the wall following algorithm was improved by using feedback control. A proportional-derivative controller was used to move the robot along a wall for at least 4 feet while maintaining a distance from the wall of 4 to 6 inches. The robot negotiated obstacles, corners and doorways with minimal contact while continuing to follow the wall. Figure 4 provides a graphical illustration of the robot's behavior requirements.

The students were to consider how this new controller affected the robot's performance with respect to overshoot, transient and steady state errors. Some student teams were able to program the robot to maintain contact with the wall around corners, out of the doorway of the classroom and down the hall in the building for at least 12 yards.

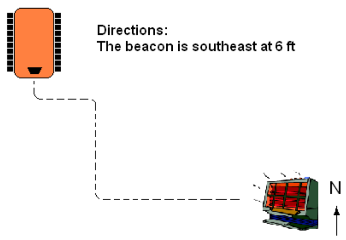
a. robot requirements b. artificial environment c. real world

Figure 4: Wall Following Example

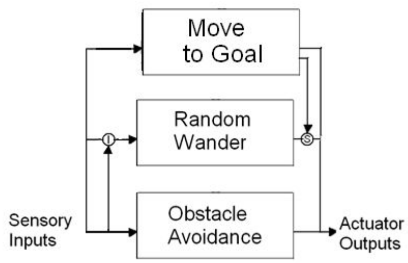
In this same lab, some students chose to improve the line following algorithm created in a prior lab by incorporating a proportional-integral controller. Due to lighting inconsistencies, odometry issues such as robot overcorrection and bandwidth limitations when polling the line sensor; this assignment was not quite as successful as the wall following. There were severe oscillations and many instances of overshooting the line. If the robot started on the line, moved slowly in order to reduce sensor aliasing and used a finite state machine to keep track of how many of the individual sensors were activated, it performed better than if it started off of the line or overshot the line and had to use a smart wander routine to find the line to follow. Most students were not able to accomplish this task on any level until the original path was greatly simplified. The students were to consider how this new controller affected the robot's performance with respect to overshoot, transient and steady state errors. Also, the students were to address the speed of circumventing the path and the ability to find the line when lost based upon the controller design.

The homing or docking lab was implemented on the mobile robot by using hybrid control. A heat beacon was placed in the robot's environment and the goal of the lab was for the robot to use a priori information about the environment to plan a path to the beacon and come within one foot of it without hitting it. The partial world map (representation) included metric distance and direction to the beacon with respect to the robot's current pose. This representation was the input to the deliberative layer of the architecture. Updates to the path were based upon sensor feedback from the distance, heading and thermopile sensors. The middle layer was used to make decisions about whether path updates were handled in the deliberative or reactive layer. The reactive layer handled obstacle avoidance. Once the robot was close enough to sense the beacon with the temperature sensor, it used this directional information to continue toward it. During this lab the students were to consider dilemmas such as what happens when there are dynamic changes to the environment while the robot executes a plan. How well did the robot respond to different starting positions and beacon locations? How could a more detailed world map improve the homing algorithm? How did to handle the compass sensor inconsistencies in the design of the homing routine?

Finally, the homing and docking lab was improved by implementing a reactive (behavior-based) control. The robot used either random wander and obstacle avoidance or a smart wander or cover behavior to move in the environment until the heat beacon was sensed. The robot would then execute a move to goal behavior based upon the information from the thermopile array. This algorithm was based upon the subsumption architecture where the obstacle avoidance was the lowest level and received the highest priority. During this lab, students were to consider how the robot's performance compared to the hybrid control. Did it find and move to the beacon quicker? Was there a real benefit in having a world model for the robot? Figure 5 presents the requirements, control architecture and images from the hybrid control lab.



a. Partial World Map Information (user input)



b. control architecture

Heat Seeking Robots (Light Bulb and Heater)

Figure 5: Homing and Docking Laboratory Assignment Images

Final Project

In spring 2009, the final project was mapping and navigation but changed to just navigation when the mapping component proved to be too difficult. The metric path planning and execution portion of the project involved using a wavefront algorithm to create a path from the robot's start position to goal location. The robot's obstacle avoidance and move to goal behaviors were used to move through the list of goals points until the robot arrived at the final destination. The algorithm used an eight-neighborhood so that the robot could move diagonally however; a four-neighborhood would have also worked. The test arena was 6 ft x 6 ft with 1 ft x 1 ft obstacles. The configuration space was an occupancy grid divided into 6" x 6" squares, where free space was denoted by '0's and occupied space by '99's. The students designed a scheme to represent the robot's start position and goal location such that these values were specified at run time. During the demonstration, the students were given the world map, generated the wavefront and planned the path from the start to goal and the robot then executed the plan. The students were graded on the ability of the robot to reach the goal while avoiding obstacles and the efficiency of the path chosen or time. Some of the strategies that the students used to accomplish the navigation task were to grow the obstacles to avoid collisions and to completely remove any spaces that the robot could not fit through from the given map in order to speed up the algorithm. Many of the students used a GUI to display the metric or topological map and all of the robot's path options. One student group actually derived an algorithm to select the path based upon minimizing steps, turns, or distance that could be selected from the GUI. Students received bonus points if they were able to use sonar and infrared sensors to create a map of the artificial environment. One student team was not only able to use the robot to make a partial world map but to use the wavefront algorithm to plan a path from a start to goal location on this map.

Conclusions and Future Work

This paper has presented the details of the implementation of an IMR course by reviewing the related literature, providing the course details and the results of the first two offerings. It is evident that designing a course to teach the history, theory and application of robotics has been a windy road. However after multiple offerings, the author is confident that the course is converging on the proper balance of theory and application. The students and instructor are slowly becoming more proficient at achieving the course goals. It is believed that students are not only gaining an appreciation for the state of the art but also having fun. They developed a realistic perspective of the mobile robot's capabilities, open areas of research and the importance of multidisciplinary teamwork. Lastly, three robotics certificate students completed the course and graduated in 2009. Two of them went on to careers in controls, robotics and automation and one went on to graduate study in robotics. The feedback from two of these students indicated that this course was helpful and relevant to their current positions. The graduate student indicated that the concepts learned in the IMR course have proven helpful in his research program. The student working in automation indicated that the format used for this course modeled the closest to his actual workplace environment.

Despite the many successes of the IMR course, there is always room for improvement. Some of the planned future work involves changing the lectures and assignments to include more research and AI theory. Research papers will be integrated into the required reading and possibly student presentations on the readings. Quizzes will be changed to closed book, closed notes and limited to ten minutes. Labs will continue to transition to higher level AI tasks. The final project will become a mapping task with localization or SLAM (simultaneous localization and mapping) and navigation. The robot controller will be changed or improved options explored to integrate the CMU camera to work with the current Serializer controller. After this change, the CMU camera will be used for a vision-based lab integrated with robot behavior and motion versus a stand-alone lab. Due to the electrical interference in the building and severe inaccuracies, the compass will be removed from future labs. Finally, students will be provided with one GUI to control and poll all of the robot's peripherals on the first day of class. This GUI will demonstrate all of the robot's capabilities in one compact form versus giving the students weekly code snippets. The reason for this change is that the students will have more flexibility in design decisions and the preferred method to accomplish the laboratory assignment requirements. This may also enable the laboratory assignments to be more open ended. There is more information about the IMR course at the course website: (http://www.rose-hulman.edu/~berry123/Courses/ECE497.html).

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