Multi-Disciplinary Senior Design Project:
A Case Study on a Multiple Mobile Robots Project

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Abstract

In this paper, we present the conduct of a multidisciplinary team senior design project at the Air Force Academy (USAFA). The procedure is presented in the context of one senior design project. The project is carried out by a team made up of two senior students majoring in computer engineering, one senior student majoring in electrical engineering, and one instructor playing the roles of a system engineering major student and a system engineering management student. The instructor's participation will help us define proper roles and academic standards for our new majors in Systems Engineering and Systems Engineering Management who will be enrolled in the senior design projects next academic year. The goal of the project is to create a group of mobile robots to search, detect, and destroy targets in an unknown environment. In addition to the design and construction of mobile robots with sensing and communication capabilities, the team must (1) solve a cooperative search problem, (2) develop appropriate communication protocols, and (3) devise strategies for multiple robots to detect and destroy targets cooperatively. To this end, each robot must operate autonomously within its environment, detect and avoid obstacles, and communicate with other robots. The project is analogous to unmanned aerial vehicles autonomously searching for and destroying targets. Once we discuss the desired learning outcomes that guided the execution of the project, we share the lessons we learned from this multidisciplinary project experience and point out important pedagogical issues observed by both students and faculty.

1. Introduction

Recently, an increasing number of higher education institutions are adopting team-based senior capstone design projects in their engineering senior design courses. The primary driving force behind the change is the requirement the Accreditation Board for Engineering and Technology (ABET) imposes for all accredited undergraduate engineering programs [1]. The requirement is a reflection of the engineering customers' (industry and, in our case, the United States Air Force) desire to hire engineering graduates who possess teamwork skills. This paper presents our collective experience, both students and faculty mentors, of conducting a team-based senior design project at the United States Air Force Academy. We present challenges associated with the administrative and technical aspects of completing a team project and share the lessons we have learned. The paper is organized as follows. In Section 3, we provide background information about the senior capstone design course at the Academy, followed by an overview of the particular team project in Section 4. Section 5 addresses the task scheduling for the large

Proceedings of the 2005 American Society for Engineering Education Annual Conference & Exposition

project involving multiple players. Sections 6 through 9 discuss technical details of the project while Sections 10 through 12 provide readers with the administrative procedures we used throughout the project life cycle and the lessons we learned. We complete this paper with a few concluding remarks.

2. Background

In this section, we briefly present the information concerning our yearlong senior capstone design course. The course is divided into two three-semester-hour courses. During the yearlong project period, students go through the same procedure one would encounter in industry to complete a complex project. For example, students must complete milestones in the form of a System Requirements Review (SRR), an Initial Design Review (IDR), a Preliminary Design Review (PDR), a Critical Design Review (CDR), and an Acceptance Test. In addition to these reviews, students also turn in writing assignments throughout the year to document their project.

During the first semester, students learn hardware and software skills related to designing, constructing, and testing complex electronic systems. The students complete their SRR, IDR, and PDR in the first semester. At the end of the semester, each project team will have completed and presented for customer approval their preliminary hardware and software designs which are completed and implemented in the second semester. The goal of the first semester course is for students to obtain practical knowledge of and experience with the initial processes important to the successful completion of design projects. These include project management, validation and organization of requirements, converting requirements to technical specifications, preliminary, high-level design, and quality assurance. In addition, students increase their knowledge of relevant engineering responsibilities and contemporary engineering issues [2].

The goal of the second semester course is for students to gain additional practical experience in the "real world" of engineering problem solving by the successful detailed design and implementation of a challenging electrical engineering project they initiated during the first senior design capstone course. The actual implementation, debugging, testing, and evaluation take place during this semester.

3. Project Overview

The systems-level goals of the project are to (1) develop efficient algorithms for multiple systems to work cooperatively and (2) design optimal communication architectures and protocols for networks of independent systems. The benefits of creating cooperative systems are obvious. By working together, a group of systems can accomplish the same task faster than a single system working alone. By working together, a group of systems can take on a task that is too complex for a single system to handle. By working together, a group of systems provide redundancy, flexibility, and effectiveness that cannot be accomplished by any single system, no matter how powerful that system may be. Exploring the potentially enormous benefits for the Air Force through cooperative robots is the objective of this project.

The required task for the students is to demonstrate cooperative behaviors of multiple agents using a small number of mobile robots. In particular, the students are required to create three mobile robots and implement a cooperative controller on each robot to find a black circular (2 inch radius) area (called the target), communicate (wireless) among the three mobile robots, and drop one 1 inch x 1inch x 1 inch cube within the circular area. Each robot must move about freely in its environment, must avoid obstacles, and must have the capability to locate itself with respect to a fixed-reference coordinate frame. One caveat is that only one robot can carry the cube. As a part of the project description, a set of 21 specific project requirements is given to the student team.

4. Project Schedule

Our capstone design sequence consists of two three-semester-hour courses taken in the senior year. The first part of the fall semester course includes some lectures with exercises to acquaint the students with the project life cycle, system test methods, and estimation techniques. Lectures include practical electrical engineering topics such as taking an electrical circuit from design to the construction of a printed circuit board as well as discussion of off-the-shelf components commonly used in projects, e.g., power supplies and regulators. The last half of the semester is devoted entirely to the students' project. The schedule for the major milestones in the robot project is shown in the table to the right. The entire spring semester course is devoted to the project with major events being the completion of the Critical (detailed) Design Review and the Acceptance Test, which are conducted according to the test plan developed by the students.

Project Milestone Schedule	
• Project Work Begins	08 Oct 04
• System Requirements Review	14 Oct 04
• Initial Design Review	21 Oct 04
• Draft Integration Test Plan	18 Nov 04
• Preliminary Design Review	09 Dec 04
• 1st Draft Technical Report	14 Dec 04
• Second Semester Begins	06 Jan 05
• Critical Design Review	08 Feb 05
• 2nd Draft Technical Report	09 Feb 05
• Begin Integration Testing	12 Feb 05
• End Integration Testing	04 Apr 05
• 3rd Draft Technical Report	11 Apr 05
• Acceptance Test	14 Apr 05
• Final Technical Report and Demonstration	13 May 05

5. Cooperative Search Problem

Initially, the three robots will be placed in arbitrary locations within a previously unknown 10 ft x 20 ft maze, with the fixed target in an arbitrary, unknown position. An operator will provide the initial robot location to the robot. Each robot is then completely autonomous, with its actions impacted by sensing its environment (obstacles and walls), sensing its location, and communication with the other two robots.

For the robots to search cooperatively, the students must develop an evaluation function for each robot to educe and encourage cooperative behavior and accomplish the required task. There are a number of desired actions from each robot to meet the end goal. First, each robot should move about in its environment while looking for a target. Thus, the evaluation function must reward the robot's movement. Specifically, we should reward the robot when it is looking around places it has not visited before. Thus, the evaluation function should reward movement of the robot to a new place, rather than simply rewarding nonproductive random movement.

This means that each robot must keep track of places it has visited within the maze. Each robot must also communicate with two other robots, letting them know its current (x-y) location with respect to a fixed reference frame within the maze and the location of any obstacles it has encountered. This will allow others to search in places where no robot has visited. Finally, a robot should receive a big reward when it finds a target and informs others of the target location. For the one robot that carries the cube, it should also be rewarded when it successfully drops its cube within the target area.

6. Communication Protocols

We simplify the communication task by allowing the students to use commercial off-the-shelf GLOLAB© wireless transmitter/receiver modules which allow each robot's microcontroller (Motorola 68HC12) to transmit/receive bytes through its serial port. The antennas broadcast omni-directionally and the robots are always in communication range. The students' challenge is to create the higher-level protocol. They must decide the content of the communication, whether the communication between robots is synchronous or asynchronous, the rate of communication updates required, and the format to pass the required information. The information transmitted is the status of every location they visit, including the location of any obstacles and the location of the target when they find it. They also must decide if authentication is necessary, if redundancy is required, and how failure of a robot (or two) will be handled.

7. Cooperative Detection/Destruction of Targets

All three robots have four sensors to detect the black circular target when they drive over it. Upon detection, they will immediately notify the other two robots of the target's location. Since only one of the robots will carry the cube to be dropped on the target, the students must develop a strategy to optimally navigate the armed robot through the known maze and must avoid any new obstacles (unknown parts of the maze) that may occur, until the target is reached. The other two robots must either ensure they will not interfere with the armed robot or if they can possibly help by exploring unexplored parts of the maze to better navigate the armed robot to the target.

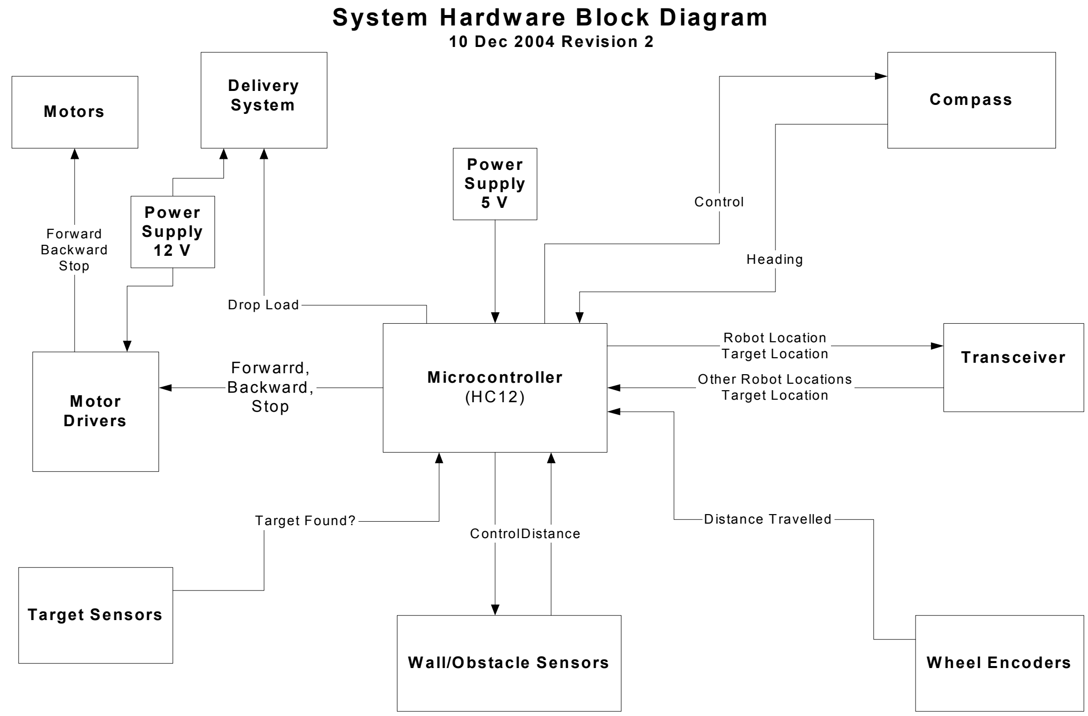
8. Robot Design

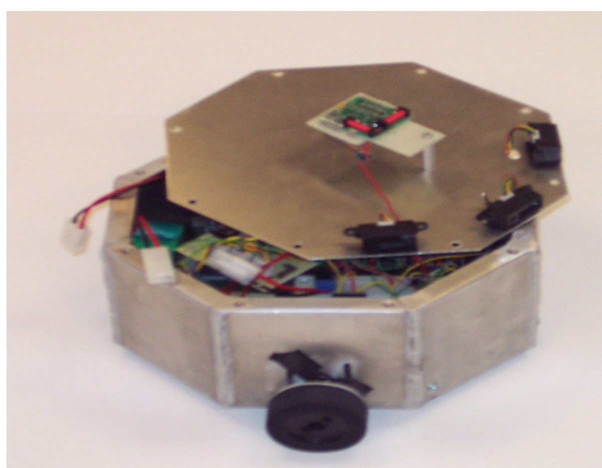
Overview of Operational Concept: The design of both hardware and software is driven by the operational concept that was developed by the students to meet the project requirements. This concept follows. The robots will start at random locations throughout a 10 ft by 20 ft search area; thus, each requires a means for being told its initial location. An outside system, consisting of a laptop, microcontroller board, and transmitter/receiver pair will accept user input to tell each robot its initial position on a grid, and then to trigger the beginning of their cooperative task. In accordance with the requirement that all computing be done by the onboard microcontrollers, user input will be limited to only the initial positioning, a start command, and a stop command. The user's system will be enabled to monitor communications, thus providing constant feedback to the user via a display of the robot positions in the search area (maze.)

The three robots will work together to find the target in the maze. After the broadcast of their initial location, each robot will also know where the other robots are. For identification, each robot will have an identification number programmed internally. This identification will also indicate which robot has the cube. Once given the start command, the robots' cooperative task begins. The maze will be divided among the robots and each will search its own section first, starting furthest away from the borders with neighboring search areas. This strategy allows the search areas to change dynamically in the unknown space between robots so that searches remain contiguous. To be efficient, each robot stores all other robots' travel and obstacles found thereby reducing the possibility of searching the same area twice. The search areas could very well require updates if robots do not search their areas at the same speeds (due to obstacles reducing the total searchable area or causing the robots to backtrack more often). Additionally, the loss of a robot would require that the remaining active robots assume responsibility for the lost robot's search area. To cooperate, they will communicate at 418 MHz using a GLOLAB transmitter/receiver pair mounted on each robot and using 6.7 in wire whip antennas. The communications protocol is robust enough to tolerate communication errors and the possible loss of up to two robots. Finally, once the target is found, the robot with the cube will navigate to the target using the knowledge of the search area it has stored to find the most efficient path. Then it will drop the cube on the target to complete the mission.

Robot Software Design: Upon power up, each robot will undergo a quick initialization, or boot-up, and then wait for the user to input its initial position. Once the robot receives and stores its initial position, it will wait for the command to begin. Each robot will make decisions about where to move based upon data collected from its sensors, search algorithms that are derived from the total system search algorithm, and information received from other robots. Control software running on the Motorola microcontroller interfaces with all onboard sensors, the transmitter and receiver, the digital compass, and the motor drivers through the microcontroller ports. After the start command is given, the robots are in a general search mode, looking for the target. Once the target is found and its location communicated to all robots, the robots will change their task to getting the payload-equipped robot to the target, and then upon payload drop, go idle.

Robot Hardware Design: At the heart of the robot is a Motorola MC9S12DP256 microcontroller, a HCS12 processor that is backwards compatible with the Motorola HC12 instruction set. The microcontroller itself is part of a larger evaluation board that has sufficient input/output (I/O) ports, jumpers, memory, and power inputs. The microcontroller is provided 5 Volts from an external source (or a battery mounted inside the robot) and is programmed from a microcomputer through its COM port. The robot communicates with other robots when the microcontroller sends and accesses data to/from its transmitter/receiver pair. The target sensors send a voltage signal to the analog to digital converter inputs which the software polls after the robot travels a specific interval to ensure that a target would not be missed. The microcontroller also interfaces independently with its wall /obstacle sensors, digital compass, motor drivers and wheel encoders, and, optionally, a second positioning sensor through various digital I/O and analog input ports. The high level design is shown below. At the PDR, the students explained their design using this drawing and a detailed drawing for each of the blocks shown below. Likewise, their high-level software design was described via a high level flow diagram.





The students also designed the prototype robot chassis shown in the picture above and presented their drawing to our educational technology fabrication technicians, who built the chassis from the drawings. The digital compass can be seen mounted on the top of the chassis.

9. Results

The preliminary results, both technical and schedule, of this two-semester project are very promising. The formal Preliminary Design Review (PDR) was conducted on 14 December

2004 during the first semester, which is a requirement of the course. The cadets demonstrated a working autonomous prototype robot that transmits data to a remote receiver and displays the data on a remote computer. The robot automatically senses obstacles and avoids them during the search mode. When an unknown target is located, the target location is transmitted to the remote receiving stations to allow cooperative destruction by other robots. The only known technical problem relates to the commanded 90-degree turns required by the search algorithm. The current search strategy assumes right angle turns; however, the current implementation does not always make 90-degree turns. It appears that a lag in the compass system is causing the problem. More testing and analysis is required to isolate and resolve this problem.

10. Status

Because of the sophistication of their operating prototype robot, the students are ahead of the normal schedule for the projects in this two-semester capstone design course sequence. In order to preclude delays due to hardware fabrication of the three robots, the students intend to conduct separate hardware and software detailed design reviews. The Hardware Critical Design Review (CDR) is scheduled for 13 January 2005 with the Software CDR following on 8 February 2005. The Acceptance Test (AT) is scheduled for 14 April 2005. To date the three students have expended approximately 180 hours on this project. This time investment by the students is almost exactly the 150 minutes per lesson that is expected by the faculty.

11. Lessons Learned

Previous project team efforts have suffered from the lack of a functioning system engineer on the team and from the engineering students' lack of interest in accomplishing and documenting the project management processes. The Academy has established System Engineering and System Engineering Management majors for the Class of 2006. Anticipating the addition of a Systems Engineering and/or a System Engineering Management major to future project teams, a faculty member was assigned to function as the Systems Engineer and System Engineering Manager for this project. It appears that one factor in the current success is the result of the System Engineer/System Engineering Manager assisting with identifying needed activities and helping schedule their logical order. Another factor is the students' only contributing the technical content and estimates for the schedule, action item lists, drawings, and briefings rather than spending the time documenting these management tools. It is premature to determine if the demonstrated success of this team, as compared to previous teams, is the result of adding an individual to accomplish the System Engineer/System Engineering Manger function. Or is it the additional leadership of the faculty member currently serving in this role? The effectiveness of adding the new majors to the design team will be assessed next academic year. A comparison of previous teams, without these majors, and future teams, with these major, is required to determine the real benefits of this team membership change. The key factors in the proposed assessment process are schedule quality and adherence, quality of systems engineering/management tools produced, and total time expended by the cadets. At least a one-year comparison will be required to obtain meaningful assessment data. Our existing assessment processes will ensure that the results produce course/project structural modifications as required.

12. Conclusion

The revisions to USAFA's Electrical Engineering capstone project are well on the way to achieving the desired results. All future projects will include at least one System Engineering major in addition to the various technical engineering majors normally assigned. USAFA's approach to the senior design capstone project has applicability to the general academic community.

Bibliographic Information

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