--

Proposal

AUTONOMOUS MULTI-ROBOT MAPPING SYSTEM

ECE4007 Senior Design Project

Section L01, The Cartel Group

Brandon Chong, Team Leader
David Esiobu
Jonathan King
Mark Nfodzo
Christopher Pau

Submitted

September 17, 2007

TABLE OF CONTENTS

Executive Summary iii

1. **Introduction** 1

    1.1 Objective 1
    1.2 Motivation 1
    1.3 Background 2

2. Project Description and Goals 4

3. Technical Specification 5

4. Design Approach and Details 6

    4.1 Design Approach 6
    4.2 Codes and Standards 8
    4.3 Constraints, Alternatives, and Tradeoffs 9

5. Schedule, Tasks, and Milestones 10

6. Project Demonstration 11

7. Marketing and Cost Analysis 12

    7.1 Marketing Analysis 12
    7.2 Cost Analysis 13

8. Summary 16

9. References 17

EXECUTIVE SUMMARY

Our project is to produce two working prototypes of an autonomous multi-robot mapping system for the U.S. Military. This is to fulfill the need of the U.S. Military to be able to accurately map urban warfare areas. The current robots that the U.S. Military uses for this function are too expensive and have too many functions. Our multi-robot mapping system will focus solely on mapping terrain and will be cheaper at an estimated price of $3,000 per robot.

The advantages of our multi-robot mapping system are the lower cost and expandability of our system. The lower cost comes from our use of cheaper parts. The expandability is the ability to add additional robots to our mapping system. Additional robots lead to increased accuracy in mapping areas and also faster mapping of terrain

The benefits of the product to the company are shown in the profit analysis. Assuming the sale of 1000 units over a period of five years, our product will bring in a 26.1% profit margin and increase profits by $781,835. Factoring in our products focus on expandability, the sales of our product could easily be higher.

By the end of our design and development stage, the team will produce two working prototypes of robots for our autonomous multi-robot mapping system. These will be fully functional and be able to create accurate two-dimensional maps of flat terrain. Two prototypes will be produced in order to demonstrate the accuracy, speed, and expandability of our mapping system to potential customers.

AUTONOMOUS MULTI-ROBOT MAPPING SYSTEM

1. INTRODUCTION

The U.S. Military needs a cheaper alternative to map flat urban terrain. To satisfy this need the project team will build two functional prototype robots of an autonomous multi-robot mapping system. The robots will use ultrasonic sensors and a rotating servo-mounted infrared sensor to collect data on walls and obstacles. The data from multiple robots will be merged to produce an accurate two dimensional map.

1.1 Objective

The U.S. Military is in need of our product to quickly and accurately map hostile urban areas cheaper. In areas like this GPS may not be feasible for an absolute location so our product will map the areas by using a relative location algorithm that involves communication between multiple mapping robots. In addition to the low price of our system, the coordination of robots and the ability to seamlessly add more robots in our system will give our product an advantage in speed and accuracy of mapping.

1.2 Motivation

The military currently uses the iRobot Wayfarer modification to iRobot's Packbot Scout for mapping urban areas. These are expensive advanced robots that include various features beyond 2D mapping. Our robot plans to specialize in 2D mapping and will be cheaper at a selling price of $3,000. Additionally, instead of using a system based on a fixed number of robots, our system will allow the addition of as many robots as needed, with each robot increasing accuracy and speed of mapping.

1.3 Background

The eBox-2300 is a miniature 200 MHz computer that runs Microsoft Windows CE. It is built specifically for its small size and ability to operate in a range of temperatures. It comes with mounting holes and is ideal for small robotic projects [1]. The eBox will be used in our product to interface from the iRobot Create to the analog sensors.

The iRobot Create is a basic programmable robot that is made for designers to build on. The iRobot Create has infrared, ultrasonic, and collision sensors and a variety of ports for interfacing to other items. The robot also has three wheels for movement and can go forward or in reverse. The iRobot Create costs around $120 will be modified to create a prototype of our product [2].

The iRobot Wayfarer is a much more advanced robot the military currently uses in urban warfare areas. This is a modification of the iRobot Packbot which integrates a SICK LMS 291-S05 indoor/outdoor laser range finder, a GPS receiver, an inertial measurement unit, and a digital video recorder. The Wayfarer can create a 2D occupancy grid of an area, in which each cell on the map shows the probability of it being occupied by an obstruction. It has capabilities to create a path through a map, avoid obstacles while traveling at up to two meters per second, record and send digital video, and patrol a selected area [3]. Our product will be cheaper and more focused on mapping than the Wayfarer.

To explore the mapping terrain our design will use ideas from [4] in which a method is described for a robot to autonomously decide where to explore based on its partial map. This method calculates a straight-line collision free path for the robot to explore. Using this strategy, the robot takes the quickest exploration path, increasing the speed of mapping. In the coordination of multi-robot exploration, [5] has created an approach to multiple robot mapping that consists of each robot exploring on their own until they encounter another robot. The robots then exchange sensor data and relative position information in order to define separate “frontiers” where each robot can explore without much overlap from the other. Their robots use a predictive model to estimate relative locations, and have complex probability algorithms to guide their exploration.

Once terrain has been explored and a partial map is created by multiple robots, the maps must be merged together. One way to do this is using the clustering algorithm called the “fusion algorithm” reported in [6]. This algorithm finds close pairs of points in and replaces them with their midpoints to create clusters. Points that are too far are discarded based on a threshold set by the user. This algorithm can be used on two partial maps to create a set of midpoints that represents an accurate merged map.

2. PROJECT DESCRIPTION AND GOALS

The iRobot Create will be modified to interface with an eBox which will interface with infrared, ultrasonic, and compass sensors. The eBox will run applications in Windows CE that will perform robot exploration, robot coordination, and sensor data mapping. Each robot will have the following properties:

- Low cost of under $3000 per robot to allow for multiple robots
- Wireless connection with other robots
- Small enough to enter standard doorways
- Automatically recharge when batteries are low
- Contain one servo-mounted rotating Infrared sensor, four static ultrasonic sensors
- Capable of recognizing other robots and determining its relative location to them

The coding in each robot must perform the following functions:

- Divide unexplored territory with other robots
- Receive sensor data and record it in a log file
- Average overlapping data to increase accuracy
- Save a current map with data from all robots to each robot when they interact
- Produce a map when robots are disengaged

3. TECHNICAL SPECIFICATIONS

Table 1. Technical design specifications.

Design Aspect	Specification
Robot Physical Dimensions	< 0.75 m x 0.75 m x 0.75 m
Robot Weight	< 15 lb
Operational Mapping Speed	One robot maps 1 m^2 / min
Wireless Communication Range	38 m indoors, 150 m outdoors
Mapping Accuracy	> 95 % accuracy
Robot Power Requirements	TBD
Robot Battery Life	2 hrs
Interface	Finished map is sent to any computer through 802.11b/g wireless connection
Autonomous	Robots explore and map area with no human interaction
Operational Temperature	0 °F - 100 °F
Operational Terrain	Flat surface
Map Type	Two dimensional map
Expandability	Unlimited robots can be added

The technical specifications in Table 1 were chosen so our product would be feasible for mapping and so our design goals would be met. The physical dimensions of the robot are kept small to keep object collisions low and to allow entry into standard doorways. The weight of less than 15 lbs will allow any adult human to pick up the robot. The mapping speed and accuracy are set so that the prototype will be comparable with the speed and accuracy of other robot mapping products. Since the system is specified to be autonomous, the interface is a specification on how data will be retrieve from the system by a human. Environmental specifications such as temperature and terrain describe conditions in which the system will function as desired.

4. DESIGN APPROACH AND DETAILS

4.1 Design Approach

The mapping system design uses an iRobot Create interfaced with an eBox mini PC and various sensors. Each robot in the mapping system will have to perform the following tasks:

- Sense the robot's environment accurately and establish its location
- Process collected data to accurately map an environment
- Wireless communication with other robots to avoid collision and share sensor data
- Wireless communication with a computer to receive initial commands
- Wireless communication with a computer to send finished map

To satisfy the requirements, the construction of each robot will follow the design shown in Figure 1.

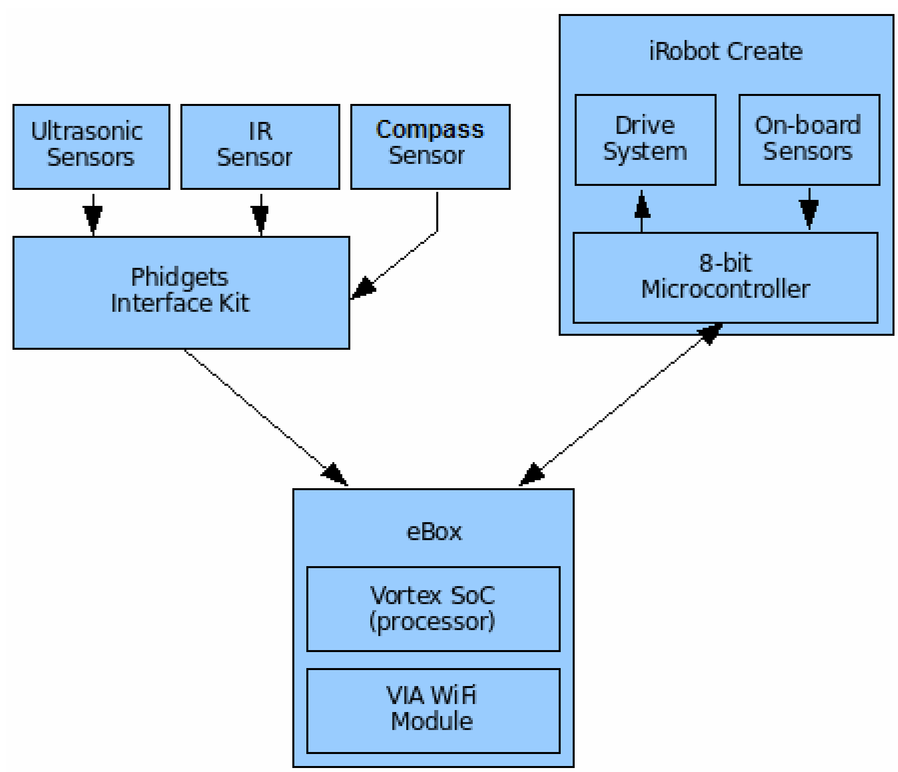

Figure 1. Diagram of components in each robot.

The details of the design will be separated into the sensor subsystem, processing and control, and the command station.

Sensor Subsystem

Each robot will use ultrasonic and infrared sensors to take distance readings. Using both infrared and ultrasonic will make the reading accuracy less vulnerable to weaknesses in either technology. Three MaxBotix LV-MaxSonar-EZ1 ultrasonic sensors will be fixed along the front of the robot with beam widths overlapping. The overlap will eliminate blind spots in the system. One Sharp GP2D12 IR range finder will be mounted on a servomechanism to take distance readings in 360° around the robot. One Dinsmore R1655 analog compass sensor will be used to take absolute heading readings. The Phidgets Interface Kit will be used to integrate these sensors to the eBox. The Phidgets Interface Kit is a board with eight analog input, eight digital inputs, eight and a USB connector. The USB connector will connect to the eBox while the other inputs and outputs will be used with the sensors. The Phidgets board has a microcontroller that controls the sensors over SPI buses, and exposes them to outside modules through a simpler API. Additionally, the iRobot Create also has several on-board sensors, including a front bumper sensor and cliff-detection IR sensors. These are accessed through the iRobot Create's internal microcontroller with its instruction set.

Processing and Control

The eBox will process all data and send instructions to its robot. The eBox will receive data from the sensors, the iRobot Create, and other robots in the system while executing the exploration, mapping, and decision making algorithms. The design approach will be to separate the robot's decision making behavior into different layers of complexity. Simpler behavior such as obstacle avoidance would be in a lower layer, while behavior such as localizing within the current map and integration of maps from separate robots would be in the upper layers.

Command Station

All robots will connect to a separate computer "command station". On this station a graphic user interface will allow an operator to initiate missions, view progress or results, and recall robots in the system. Communication will take place on a wide area network, or the internet for very remote operations. Details of implementation are to be determined.

4.2 Codes and Standards

Several communication protocols will be used to integrate the various parts of the mapping system. Each sensor on the Phidgets board will use an SPI bus to talk to the on-board microcontroller and will also use USB to connect to the eBox. There are four signals on an SPI bus: a clock (SCLK), a serial data in (MOSI), a serial data out (MISO) and a select line used to select the destination peripheral (SS). Three line variants, where a single data line servers both directions are also common [7]. Data is sent in byte-sized words, delimited by special start and stop transitions defined on both the clock and data lines. The lines are required to float high, and this typically done with pull-up resistors and the terminals [7].

USB connectors have four lines: a reference voltage (VBUS), ground, and two data signals D+, and D-. Stated in [8] is that the two data lines are used for differential signaling, so bits are represented by the voltage difference on the two lines. The differential voltage makes the bus more resistant to noise, and allows devices to use lower voltages than might normally be required. USB communication also specifies a complex set of communication rules, and device architecture requirements. These communications require USB drivers that come with the Phidgets board.

4.3 Constraints, Alternatives, and Tradeoffs

The design was focused on cost and ease of hardware implementation. Using parts that interface easily allows more time to be spent developing the software and researching its complex algorithms. Initially, the design was to build each robot. However, preliminary research showed that each robot would cost nearly $100 in parts and require large amounts of time to design and construct. The iRobot Create robot was chosen instead as the development platform because it would be comparable in cost and perform all the functions desired by the design.

In searching for a range finding sensor, the design team considered laser, infrared, and ultrasonic. Laser is more accurate than both ultrasonic and infrared, but typically at least ten times as expensive. Infrared and ultrasonic sensors are accurate enough for the design, but have weaknesses. Infrared sensors are sensitive to the material type and can be limited by range. Ultrasonic sensors take distance readings at a lower rate than infrared. The proposed design will use both infrared and ultrasonic sensors to cover these weaknesses. A single, servo-mounted infrared range finder will be used instead of several fixed infrared sensors. This is because it will allow distance sensing in 360° around the robot at a lower cost of one infrared sensor and one servo. The fixed sensors would allow faster sensing, but would be more expensive and less flexible in range. A servo-mounted ultrasonic sensor was also considered, but the slower sensing of a rotating sensor along with the lower reading rate of the ultrasonic sensors was too slow. Therefore, the design will use four ultrasonic sensors on the front of each robot.

The design team considered not using a compass sensor to save on costs, but it was not feasible. Since the mapping system relies on knowledge of each robot's relative position, there was already a possibility of error from mechanical and sensor sources. To reach the specified mapping accuracy, the absolute heading from a compass sensor was needed.

5. SCHEDULE, TASKS, AND MILESTONES

ID	Task Name	Duration	Start	Finish	Predecess
1	Define Scope of Project	9 days	Mon 8/20/07	Thu 8/30/07	
2	Determine and Purchase Necessary Parts	10 days	Fri 8/31/07	Thu 9/13/07	1
3	Construct Robot	7 days	Thu 9/20/07	Fri 9/28/07	2
4	Ebox interfaces with Robot and Accurate Sensor Data	0 days	Fri 9/28/07	Fri 9/28/07	3
5	Design PC Plotting Program	25 days	Thu 9/20/07	Tue 10/23/07	
6	Design WinCE program to move Robot	14 days	Thu 9/20/07	Tue 10/9/07	
7	Autonomous Movement of Robot	0 days	Tue 10/9/07	Tue 10/9/07	6
8	Design Search and Data Acquisition Algorithm	14 days	Wed 10/10/07	Fri 10/26/07	7
9	Wireless Communication between Robot and PC	6 days	Mon 10/29/07	Mon 11/5/07	5,8
10	Floor layout obtained with One Robot	0 days	Mon 11/5/07	Mon 11/5/07	9
11	Syncronization of Data from different robots	5 days	Tue 11/6/07	Mon 11/12/07	10
12	Final Testing and Debug	10 days	Tue 11/13/07	Mon 11/26/07	11
13	Weekly Progress Reports	74 days	Mon 8/27/07	Wed 12/5/07	
14	Written Proposal	6 days?	Mon 9/10/07	Mon 9/17/07	
15	Draft Project Summaries	10 days	Tue 9/18/07	Mon 10/1/07	
16	Final Project Summary	7 days	Tue 10/2/07	Wed 10/10/07	15
17	Web Site	10 days	Thu 9/27/07	Wed 10/10/07	
18	PDR Presentations Finished	7 days	Thu 10/11/07	Fri 10/19/07	
19	Final Project Report	15 days	Thu 11/15/07	Wed 12/5/07	
20	Final Project Demonstration	7 days	Tue 11/27/07	Wed 12/5/07	12
21	Final Project Presentation	15 days	Thu 11/15/07	Wed 12/5/07	
22	Completion Date	0 days	Wed 12/5/07	Wed 12/5/07	19,20,21

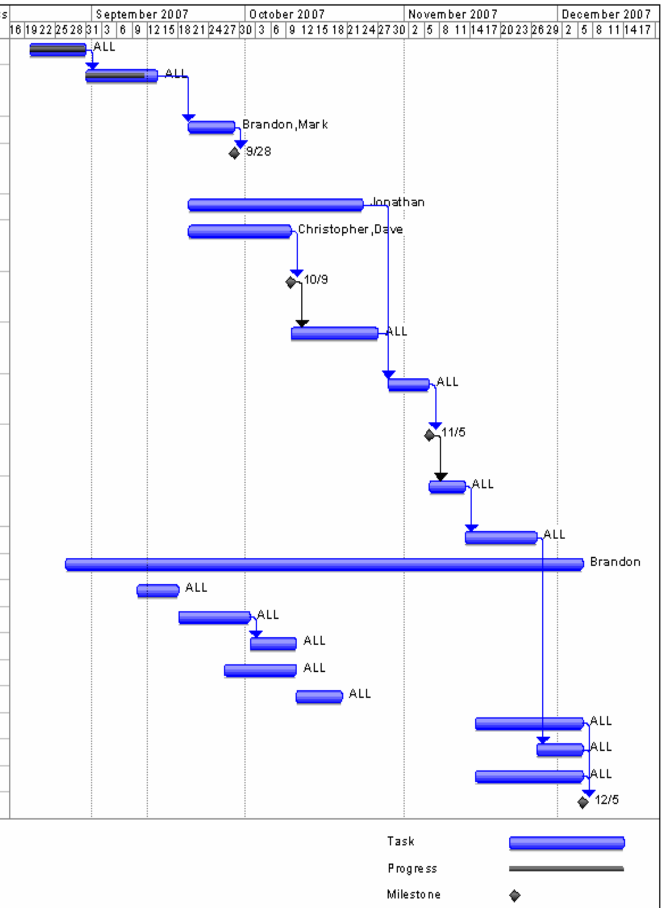

Figure 2. GANTT Chart showing project task completion dates.

The GANTT chart in Figure 2 shows how the project is divided up into multiple tasks. The length of each task was estimated based on the difficulty of the task. The team will be divided into a hardware and software group based on each member's specialization. Christopher, David, and Jonathan will focus on the software development while Brandon and Mark will work on hardware issues for the robot. When Brandon and Mark have completed the hardware tasks they will also focus on software development. To stay on schedule the team will meet on every Wednesday to discuss problems and progress. Team members working on the same task will meet when needed.

6. PROJECT DEMONSTRATION

Prototype testing will be done in an empty room in the Van Leer building. The two prototype robots will be released into the room with commands to start from the command station. These robots should autonomously explore the room taking sensor readings. Each robot will be sending its partial map data to the command station through the eBox's wireless transmitter. A map will be created and displayed at the command station using the PC plotting program. To validate progress in the prototype's mapping ability, the map will be compared with physical measurements of the room to calculate the accuracy of the system.

The final demonstration will be a video recording of the prototype testing process along with other tests. The prototype testing process will be run with one robot and with two robots. After the map is created from each mapping process, it will be displayed side-by-side with an accurate floor plan of the room. The accuracy of each map will be calculated by comparing dimensions of the room, orientation of the map, and differences in object positions. After this, specific tests for each of our technical specifications will be shown.

7. MARKETING AND COST ANALYSIS

7.1 Marketing Analysis

The U.S. military uses state-of-the-art multifunctional robotics for mapping of urban areas. An example of one of these robots is the iRobot Wayfarer. This is a tread mounted robot that has a laser range finder, a GPS receiver, an inertial measurement unit, and a digital video camera among its features. The Wayfarer is controlled by soldiers to map terrain, map paths through the terrain, patrol areas, and send digital video for reconnaissance. However, an expensive price comes along with all the equipment and functions.

Our product will be specialized for mapping and will be sold at a much lower price. Instead of an expensive laser range finder, GPS receiver, and digital video camera, our robots will have only cheap analog sensors for our mapping measurements. Our system will also be autonomous after issuing an initial start command. This allows the robots to map areas, such as hostile territory, that would be dangerous for soldiers to map themselves. The technological advantage of our product is the ability to seamlessly add more robots to the mapping system. Many multi-robot systems today use a fixed number of robots that have certain functions for each robot. Our system will allow for expandability of robots that can coordinate with each other regardless of the number of robots in the system. More robots can perform more measurements, map faster, and create more accurate maps.

7.2 Cost Analysis

Table 2. Development cost of two prototypes.

Parts	***1,554***
Labor	***19,200***
Fringe Benefits, % of Labor	4,800
Subtotal	25,554
Overhead, % of Matl, Labor & Fringe	14,055
Total	$39,609

Table 3. Selling price and profit analysis (based on 1000 units sold).

Parts Cost	***777***	
Assembly Labor	***12***	
Testing Labor	***26***	
Total Labor	38	
Fringe Benefits, % of Labor	10	
Subtotal	825	
Overhead, % of Matl, Labor & Fringe	453	
Subtotal, Input Costs	1,278	
Sales & Marketing Expense	750	
Warranty & Support Expense	150	
Amortized Development Costs	40	
Subtotal, All Costs	2,218	
Profit	782	26.1%
Selling Price	***3,000***	
Total Revenue	$3,000,000	
Total Profit	$781,835	

Table 4. Breakdown of parts cost for two prototypes.

Part	Quantity Purchased	Unit Cost	Total Cost
Rechargeable Battery	2	$80.00	$160.00
Servo	2	$12.00	$24.00
iRobot Create	2	$135.00	$270.00
eBox	2	$240.00	$480.00
Sharp GP2D12 IR Range Finder	2	$30.00	$60.00
Dinsmore R1655 Compass Sensor	2	$30.00	$60.00
LV-MaxSonar-EZ1 Ultrasonic Sensor	8	$30.00	$240.00
Phidget Interface Kit 8/8/8	2	$80.00	$160.00
Mounting, Cables, and Packaging	2	$50.00	$100.00
Total Material Cost			**$1554**

Table 5. Breakdown of labor costs.

Employee	Average hours per week	Numbers of weeks*	Total hours	Rate per hour	Total salary without fringe benefits	Fringe benefits (25%)	Total salary with fringe benefits
Mark	12	16	192	$20	$3840	$960	$4800
David	12	16	192	$20	$3840	$960	$4800
Christopher	12	16	192	$20	$3840	$960	$4800
Jonathan	12	16	192	$20	$3840	$960	$4800
Brandon	12	16	192	$20	$3840	$960	$4800
					Total salary with fringe benefits		**$24000**

The above tables show a cost analysis of our design in mass production of 1000 robots. Table 4 shows that it will require $1,554 for the parts required to build two prototypes. The rechargeable battery and iRobot Create prices came from the iRobot website [9]. The sensor prices are estimated after checking prices of various different infrared, ultrasonic and compass sensors. The eBox and servo prices were quoted from Professor James Hamblen, a computer engineering professor at Georgia Institute of Technology who specializes in embedded systems [10]. The Phidgets Interface Kit price was from the Phidgets website and we estimated the price of mounting, cable, and packaging to the best of our ability [11]. All our parts price estimates include adjustments for tax and shipping.

Table 5 shows our estimates for the cost of labor. There are five people in the team and each is expected to put in 192 hours at $20.00 per hour giving us total labor of $19,200 on the project. We determined fringe benefit costs of $4,800 by taking 25% of the total labor cost. We calculated the overhead costs of $14,055.00 by taking 55% of the cost of labor, parts, and fringe benefits of labor. The total development costs come to around $40,000 and are listed in Table 2.

Our profit analysis is shown in Table 3. The parts cost for one robot is estimated as half of our parts costs for two robots. The development costs come from the total in Table 2, and the testing and assembly labor costs are estimated to the best of our ability. All the other costs are derived from this information on the table. The final cost for each robot comes to $2,218. We set our selling price to $3,000 to keep the price low but still profitable at 26.1% profit and $782 of profit per robot. This allows us to underbid the expensive robots the military currently uses and to allow our customers to use the expandability of our system by purchasing multiple robots. Over a five-year period selling 1000 robots the total profit comes out to $782,000.

8. SUMMARY

The project is currently in the design phase. We have researched many exploration, mapping, and coordination algorithms and are deciding on which ones to modify and use. We still need to design software applications for our product for all the functions of the robot. We have placed an order for all the hardware that will be used in our project. We believe all this hardware should be compatible and usable in the manner stated in our design approach. Once the hardware arrives our team will immediately begin working on getting all the parts functional and connected. We will also begin mounting all the hardware on the iRobot Create. We will put up the team website soon to display our progress.

9. REFERENCES

[1] "eBox-2300 Compact PC," [Online document], [cited 2007 Sep 14], Available HTTP: http://www.embeddedpc.net/eBox2300/tabid/110/Default.aspx.

[2] "iRobot Create Programmable Robot," [Online document], [cited 2007 Sep 14], Available HTTP: http://www.irobot.com/sp.cfm?pageid=305.

[3] "Wayfarer," [Online document], [cited 2007 Sep 14], Available HTTP: http://www.irobot.com/sp.cfm?pageid=146.

[4] F. Amigoni, V. Caglioti, and U. Galtarossa, "A Mobile Robot Mapping System with an Information-Based Exploration Strategy," In Proc. of the First International Conference on Informatics in Control, Automation, and Robotics 2004, 2004, pp. 71-78.

[5] D. Fox, J. Ko, K. Konolige, B. Limketkai, D. Schulz, and B. Stewart, "Distributed Multi-robot Exploration and Mapping," In Proc. IEEE 2006, 2006.

[6] D. P. Dobkin and A. Tal, "Efficient and Small Representation of Line Arrangements with Applications," In Proc. of the Symposium on Computational Geometry, 2001, pp. 293-301.

[7] Motorola, Freescale Semiconductor, SPI Block Guide V03.06, February 2003, Freescale Semiconductor Inc.

[8] Compaq Computer Corporation, et al., Universal Serial Bus Specification, Revision 2.0, April 2000, Compaq, HP, Intel, Lucent, Microsoft, NEC & Philips.

[9] "iRobot Store," [Online document], [cited 2007 Sep 14], Available HTTP: http://store.irobot.com/home/index.jsp.

[10] Hamblen, J. Personal interview. 5 September 2007.

[11] "PhidgetsInterfaceKit 8/8/8," [Online document], [cited 2007 Sep 14], Available HTTP: http://www.phidgets.com/products.php?product_id=1018.