TEAM SPOT:

A multidisciplinary team approach to the

design and development of an autonomous mobile robot team.

Submitted By
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In particular, I would like to acknowledge and thank my fellow Team Spot design team members, Emily Mower and Laurel Hesch. Emily and Laurel provided the computer and electrical engineering expertise necessary to successfully complete our project by endowing our robots with their sensing, reasoning and communication abilities.

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Abstract

In this thesis I address the design, development and success of Team Spot, a team of three autonomous robots that seek and locate a spot of light. I will also discuss the motivation for developing a team of target finding robots and the advantages and disadvantages of using light as the robots' target. The combination of robot types (mobile and stationary) will demonstrate that, similar to teams of humans that collaboratively solve problems, a team of various specialized robots also has enhanced problem solving capabilities. The successes, limitations and failures of Team Spot will be discussed throughout each design and development phase.

The resulting team of robots was able to find the light 83% of the time and in fewer than 3 minutes. They were severely hampered by surrounding light and the mobile robot drifted to the right by several degrees while traveling to the spot of light.

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Chapter I

INTRODUCTION

Background

Robots may perform tasks that humans consider menial, repetitive, or hazardous. The necessary mechanical components to build robots have been available for some time. However, powerful computerized components necessary to effectively operate robots have not been available until recently. Certain technologies, such as electrical communication devices, sensors, and microprocessors are currently being produced with a broad and powerful range of capabilities. The field of robotics is undergoing a period of resurgence because these components allow for the production of increasingly intelligent and capable robots.

Mobile robots are now being designed to perform a variety of tasks where they must be able to communicate with their controllers and with other robots. In particular, teams of autonomous mobile robots must communicate with human controllers and with other robots in their team. The communication capability necessary to interact with humans and other robots is now available because of developments in wireless communication devices.

In addition to increased communication capability, the development of a smart chemical, “sniff,” sensor has led to the idea that a team of robots can be developed that protects public areas against hazardous chemical releases. A team of robots with this sort of sensor technology can ultimately be designed to accurately locate and possibly contain accidental or intentional chemical threats. Robots designed to carry chemical sensors have a variety of design requirements including effective housing of sensors, communications equipment, and microprocessors. Overriding such a design is the need to maintain an agile body design.

When designing a team of robots, the design of the members of the team is only effective if the design works with the other robots in the team. A team of robots that seeks and locates a chemical threat will have a variety of capabilities. Each robot will have the capacity to communicate location and sensor data with the other robots in the team. These robots also will communicate with their host, which is referred to as the mother or master robot. Some of the robots comprising the team will be mobile and others will be stationary. Mobile robots will be able to independently travel to the location of the chemical source and communicate its geographical coordinates. Stationary robots will tell the strength of the chemical source and its position. The design of the mobile and stationary robots will differ to meet their specific purposes. Both robots will have a compact and robust design that withstands various environmental hazards. Design and development of such robotic systems is cost intensive and demands knowledge from a range of engineering disciplines.

In the development of a robot team, low-level prototyping is needed. The ROBOTable has an interactive table-top screen (Figure 1) that records the movement of one or more robots and transmits the position and actions of the robot(s) to a distant table and its operator(s). The ROBOTable allows robots to be designed, controlled and tested in a collaborative distance learning environment. The ROBOTable offers control features, and a view of control objects as they are manipulated in real time.

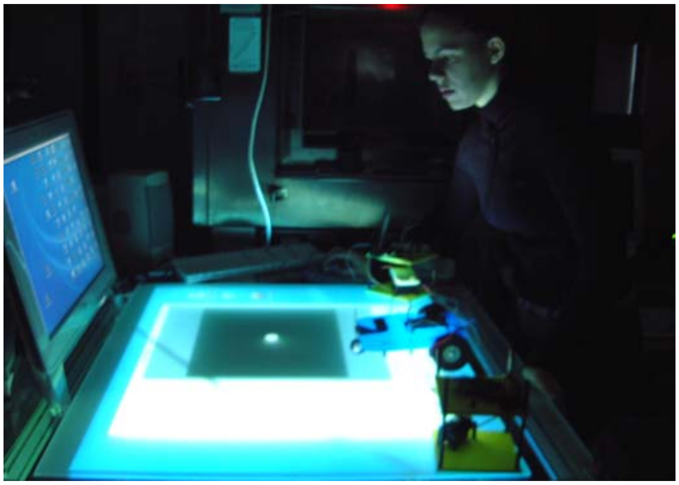


Figure 1: The ROBOTable

In this project a team of robots will be designed with the capacity to work on the ROBOTable. The ROBOTable will test the performance of the robotic team in a constrained environment. In addition, the ROBOTable will provide an environment in which a target can be exposed to the robots in a variety of positions that can be replicated over time. The robots can effectively sense and seek the target and communicate its coordinates to robotic team members and human controllers. The size of the ROBOTable is a design constraint in the development of an autonomous mobile robot team.

In this project, a multi-discipline team of undergraduate engineering students worked together to collaboratively design, prototype, and test a team of robots. The design team is composed of three students: a mechanical engineering student (the author) and two electrical and computer engineering students (Laurel Hesch and Emily Mower). The design team developed Team Spot, a team of autonomous robots that seek and locate a spot of light.

For the purposes of this project the design team chose to build a team of light sensing robots. Though the idea of chemical sensing robots provided inspiration for the project, it is not possible to build and prototype such a team within an academic year. A team of chemical seeking robots requires expertise in the fluid mechanics of plume flow, as well as an understanding of the complex electronics and chemistry used in the chemical sensors. Light sensors are cheap, readily available and are able to locate the concentrated emission center of a target, similar to the chemical sensing problem.

Significance of the Project

Possible applications of autonomous robot teams are vast. Imagine a team of mobile and stationary autonomous robots sent to Antarctica to explore a largely unknown and harsh environment. The stationary robots will define polygonal areas and then send mobile robots to collect data throughout the defined regions. The mobile and stationary robots will communicate their coordinates relative to each other and the team's mother robot will communicate its coordinates relative to the planet. Over time, the team will compile their position data which can be used to map the exploration area. For this robot system to work effectively, design and engineering of all parts of the team must be interdependent. No part of the system can be designed independent of the whole. This makes the design of the team necessarily a multi-discipline process.

Another example, discussed earlier, is an autonomous mobile robot team used to detect and clean up toxic chemical spills. Once again, such a team will consist of stationary and mobile robots. All robot team members will be equipped with chemical sensors designed to locate the coordinates of a chemical release. The stationary robots will define the area of the release and send mobile robots to locate its specific location. Ultimately, robots can be developed with the ability to contain the chemical release, thereby limiting toxic exposure to humans.

Statement of Purpose

I propose the development of an autonomous mobile robot team: Team Spot. Team Spot's goal is to locate and transmit coordinates of a target (a light spot), send a robot to the target, and follow the target as it moves. Team Spot will be designed for testing and use on the ROBOTable.

Design Requirement

Designing and building Team Spot requires knowledge from mechanical, electrical, and computer engineering disciplines. The design team must jointly determine the electrical requirements, an elegant light finding algorithm, and a compact and agile mechanical body. The design team will outfit the robots with light sensors able to determine the direction of greatest light intensity. Accurate determination of the light data is crucial in allowing the stationary robots to locate the coordinates of the light source and the mobile robot to travel to the origin of the source. As the mechanical engineer working on the project, the author of this paper must focus primarily on the mechanical aspects of design.

The projection area of the ROBOTable is 37 by 29.5 inches, approximately three by two and a half feet. There is a six inch border around the frosted glass projection surface, but no rim barrier encompassing the tabletop. The robots must be programmed to operate within the dimensions of the table or with the ability to detect the tabletop's edge.

Team Spot's individual robots must effectively use light sensors to detect the intensity and direction of the light source. Development and placement of the light sensors is crucial to the light spot location effectiveness. The placement of light sensors on the mobile and stationary robots will differ due to the variations in robot purpose. The robots' light sensors must be able to distinguish fine distinctions in light intensity values.

Each robot's microprocessor must operate autonomously. The microprocessor must be able to send and receive data from all components. The microprocessor and communications device must also be able to send to and receive data from other robots. To ensure continuity of data passed between robots, all robots in the team must have the same microprocessor.

A mobile robot's operation environment is the foremost design consideration. A well designed mobile robot must be able to optimize function with travel within the defined environment. Though a good robot design is economical, it must also be robust enough to withstand the hazards of its environment. The mobile robot should not have capabilities beyond the scope and requirements of its operating environment. A mobile robot design effectively houses motors, sensors, and communication components. It is also agile and durable. The movement mechanisms must be housed in a manner that maximizes sensing and communication capabilities, while not limiting maneuverability. The motors must allow for forward and backward motion and have enough torque to turn sharply. A well-designed mobile robot is simple, yet functional and durable. It is able to achieve maximum performance within its operating environment.

Stationary robots operate upon a fixed base or from a fixed position. The underlying function of mobile and stationary robots differs. Mobile robots "go to," "find" or "map" something in a defined area. Stationary robots perform some operation from a certain fixed position. Stationary robot components may move, but the robot itself remains in a fixed location. Team Spot must be comprised of both stationary and mobile robots. The stationary robot(s) must use sensors to determine the approximate location of the target and then send the location data to the mobile robot(s). Utilizing an on-board microprocessor, the mobile robot(s) must process the position data sent by the stationary robot(s) and use the resulting coordinates to determine an appropriate path of travel. Should the mobile robot(s) fail to find the light spot, it must have the autonomous capability to re-locate the target or follow the target as it changes position.

Team Spot robots must be autonomous. Autonomous robots perform operations under the direction of an onboard microprocessor, and do not require data processing by a host computer. Although Team Spot robots send and receive some information, each robots actions are determined its own microprocessor.

Thesis Statement

An undergraduate engineering design team will collaborate to design and develop a team of light finding robots: Team Spot. Team Spot will consist of stationary and mobile robots which will gather and communicate information on the position of a light source on the ROBOTable. Team Spot will have an effective mechanical design, which houses electrical circuits, microprocessor, and communications hardware. The design will be appropriate to teams' operating environment.

CHAPTER II

PROJECT OUTCOMES

Introduction

The development of Team Spot required a succession of design phases to take it from project concept through final design. Three solutions were proposed and discussed. A configuration consisting of two stationary robots and one mobile robot was agreed upon as the most efficient solution. Robot design differed between two stationary robots and one mobile robot to better support their individual functions. Each robot design was tested, manipulated, and redesigned to meet design team standards. All phases of Team Spot's development were tested in several darkened settings: the ROBOTable with a light spot projected onto the tabletop screen, a concrete floor with a flashlight for the light spot, and the TUFTL source room with a flashlight for the light spot.

Success was defined as Team Spot's ability to accurately identify and communicate light spot coordinates and send the mobile robot to that location. The mechanical design of the robots met the requirements specified in the project proposal. The mobile and stationary robots housed all components and did not interfere with light sensing or communications equipment. The mobile robot was agile and compact and able to maneuver around the ROBOTable, as well as on concrete, tile, linoleum and carpeted floors. The stationary robots were able to locate the light spot 83%, communicate that spot to the mobile robot 91% of the time and drive to the correct position 50% of the time. The multi-disciplinary nature of the design team was successful in that it provided an ongoing collaborative design process in which design was conducted with the whole project in mind.

Problem Breakdown and Initial Solutions

Brainstorming and development of an initial solution began by breaking Team Spot's design requirements into its fundamental mechanical, computer, electrical, and usability elements. The requirements and limitations of each of these elements led to the decision that Team Spot must perform as a combined team of mobile and stationary robots that seek a spot of intense light.

A single spot of light was chosen as Team Spot's target because of its similarities to a chemical source. Both chemical and light targets are most concentrated at their source. The location of either target can be found by looking for the location of greatest intensity. A growing light spot, multiple light spots, and a moving light spot were also considered as possible problems for Team Spot to solve.

Similar to a fluid plume that expands and wafts outward as it moves further from a chemical source, the gradient of a growing spot of light grows outward from the source with decreasing light intensity. The solution to finding a growing spot of light is a continuum of the solution to finding a single spot of light. Once the robot finds a spot on the gradient of light, it will follow the gradient towards brighter and brighter light until it finds the center of the spot.

A problem involving multiple spots of light is another extension of the single spot problem. In this situation, light spots of varying intensity can be illuminated in several locations. The robot team is expected to find and prioritize the light spots based on intensity.

A robot from the team will travel to the light spot with greatest intensity and then to all the other light spots (in order of light intensity). The multiple spot solution is based on the robot being able to find a single spot of light.

A moving light spot was also considered. This problem involves the team finding a single spot of light and following the spot of light as it moves. The simplicity of the algorithm involved in finding a single spot of light over multiple light spots, a growing light spot, or a moving light spot made the single spot problem attractive. The single spot problem served as a good base point to begin development of Team Spot. Because it is the base point of all rejected problems it allows for expansion to solving these more complex problems.

Robot Components

Using light sensors to find a spot of light is an obvious choice. Simple photo-resistors measure the intensity of light viewed by the robots. The autonomous nature of the robots requires each to have its own microprocessor. The Pic line of microprocessors is programmed in Basic, a very common object-oriented programming language. Basic and Pic processors are commonly implemented in electrical projects. The OOPic-R board (Appendix A, Figure 14) was chosen for use in all of the robots. It has several LEDs, an A/D converter, a 5 Volt voltage regulator, and 16 data pins. This compact electrical package enhanced the simplicity of the robots. The OOPic-R board eliminated the problems inherent with self-built boards and thus sped up the electrical, communications, and mechanical development of the robots.

Figure 2: OOPic-R Microprocessor Board

Problem Solutions

Three types of robotic teams were considered for Team Spot design. At this stage, Legos were used to prototype the chosen team configurations.

Solution 1: Three Robots (2 stationary; 1 mobile)

This solution has a configuration of three robots: two stationary robots and one mobile robot. The two stationary robots scan 90 degrees and determine the angular position containing the greatest light intensity. Then, via an infrared, radio frequency, or a Bluetooth device, a stationary robot sends the position of greatest light to the mobile robot. The mobile robot then calculates the coordinates of the light spot and drives to that position. To check that it has traveled to the correct position, the mobile robot scans 360 degrees, looking for a spot of greater light intensity. If it detects a light spot of greater intensity, it will drive toward the spot. Once the light spot is located and confirmed, the mobile robot communicates that it has located the light spot and, if possible, communicates the spot's coordinates.

Problems with this solution could occur if the stationary robot reports the coordinates of interfering ambient light. The angle of the interfering light detected by one robot, and the angle of the actual light spot detected by the other robot may not intersect. This data will prevent the mobile robot from determining the x and y coordinates of the target spot.

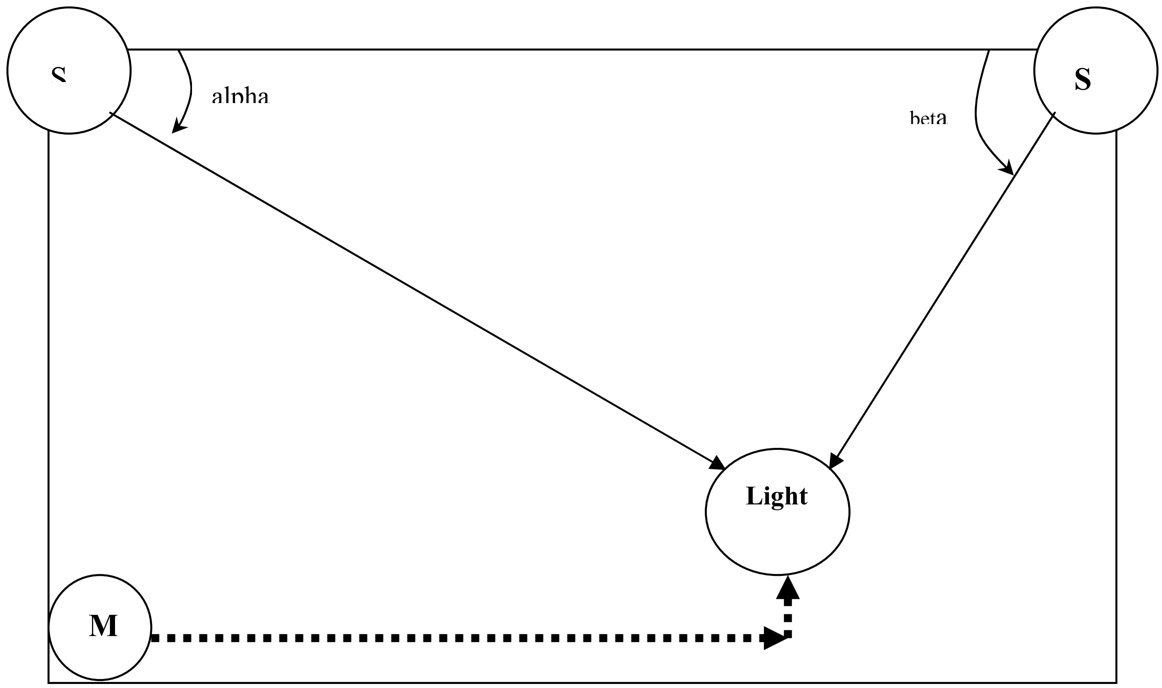


Figure 3: Illustration of Solution 1 - Team Spot Configuration: 2 stationary and 1 mobile robot(s)

Solution 2: Three Robots (2 scanning; 1 mobile robot)

This solution uses three robots: 2 scanning robots and 1 mobile robot. The two scanning robots have the capability to move along a track, scanning the horizontal base (x-axis) and vertical side (y-axis) of the ROBOTable. They determine the x and y coordinates of greatest light intensity and communicate this position to the mobile robot. The mobile robot travels to the x and y position and then scans 360 degrees to check for light spots of greater intensity. Once the mobile robot confirms that it has located the light spot, it communicates its coordinates.

Possible problems in this solution occur in the behaviors of the scanning robots. The scanning robots drive along the bottom and sides of the ROBOTable. Their outbound and inbound scanning path must be repeatable and in a straight line. As the ROBOTable does not have a barrier at its edge, there is a chance for the stationary robot to drive off while scanning. This solution will take longer than the first solution

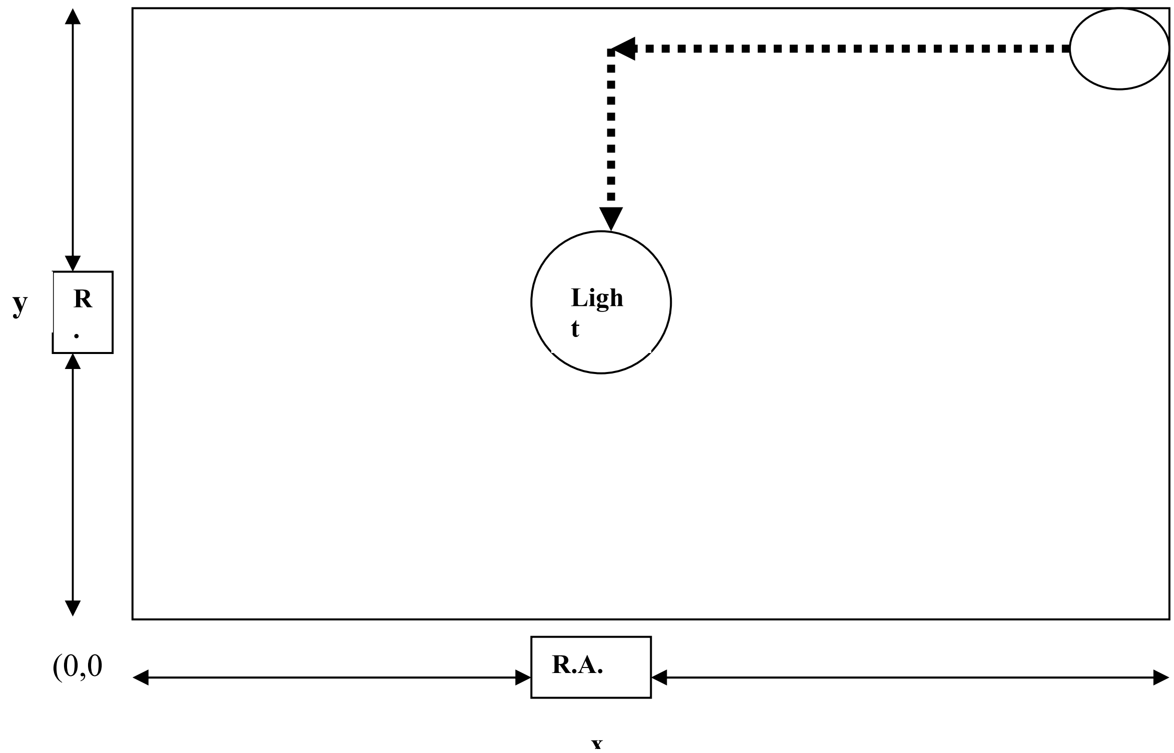


Figure 4: Illustration of Solution 2 - Team Spot Configuration: 2 semi-stationary; 1 mobile robot

Solution 3: Four Mobile Robot System: 4 Mobile Robots

This solution employs a quadrant system and requires the most simplistic robot behavior. Four mobile robots operate with the same algorithm and depend on each other in each stage of light searching. The robots start at the corners of the ROBOTable, take a light reading, and communicate their light intensity value to each other. The robot with the greatest light intensity remains in its initial position, while the other three robots advance to the corners of the quadrant containing the light spot. This quadrant is sub-divided into four quadrants and the robots repeat the algorithm. All four robots converge on the light spot and report its coordinates.

This solution is the most simplistic in terms of robot behaviors, but it is the most time-consuming in terms of robot operating time. It also has the greatest margin for error. Should the robots be unable to find the light spot, they have no method to backtrack to their initial positions. Additionally, if one robot malfunctions, the entire team is handicapped. The robots in this solution are not completely autonomous, because they cannot operate independently of one another and the success of the team depends so highly on the success of every member.

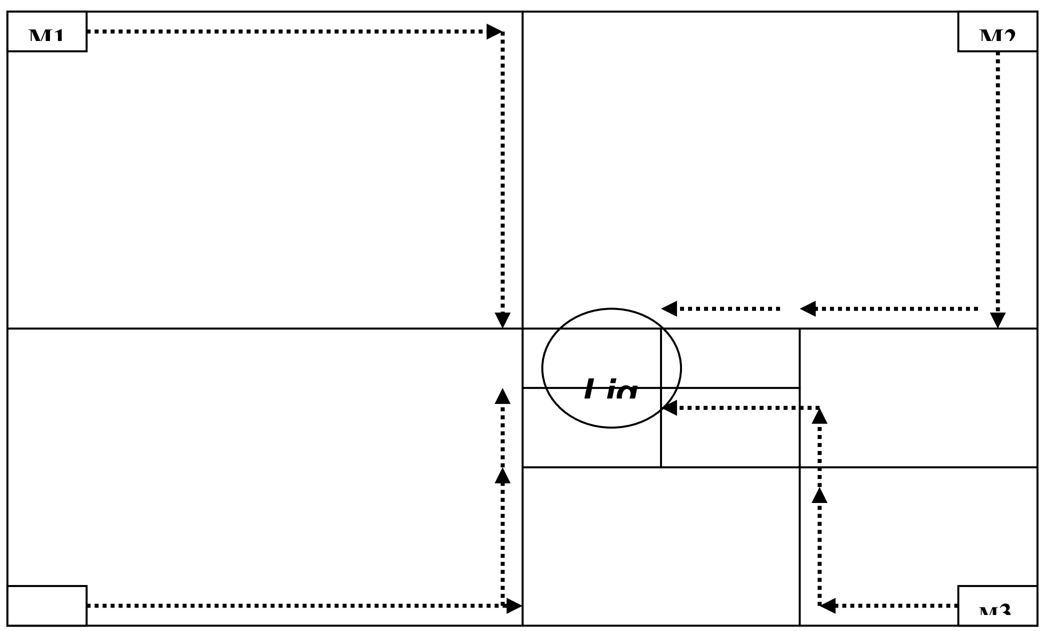


Figure 5: Illustration of Solution 3 - Team Spot Configuration: 4 mobile robots

Chosen Solution

A mobile and stationary robot team was developed with Legos (Figure 6,7). Light sensors were employed to collect light intensity data and infrared communication was used to transmit data between the robots. From experimentation with this basic prototype, it was determined that Team Spot would utilize the first solution, a team of two stationary robots and one mobile robot.

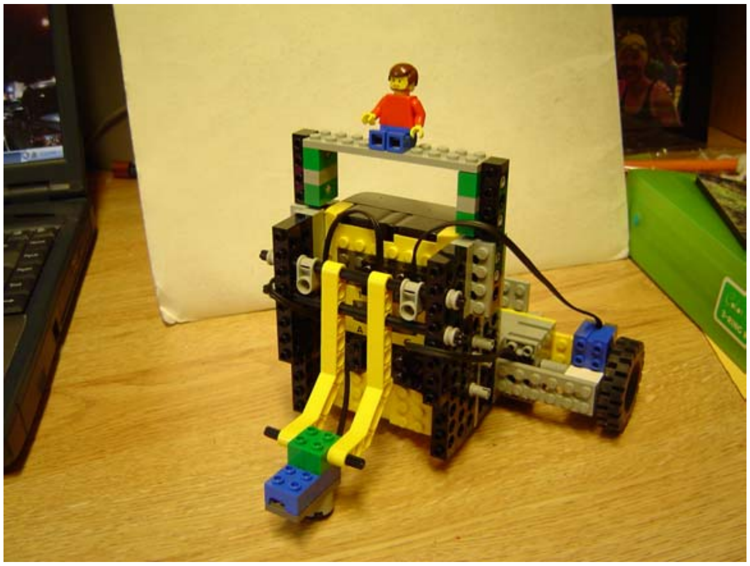


Figure 5: Mobile Lego Robot

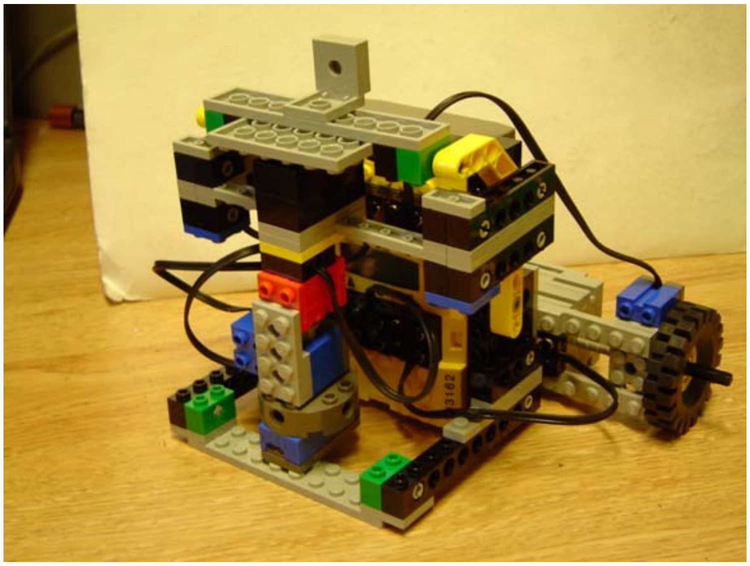


Figure 6: Stationary Lego Robot

First Prototype

A team of two stationary and one mobile robot was constructed.

Robot Components:

- OOPic-R Microprocessor
- Infrared transmitter and receiver with electronic bred boards
- Photo-resistors (light sensors) with electronic bred boards
- Motors for rotation of light sensors (Stationary Robots Only)
- Motors for Mobility of Mobile Robot
- LCD Display

An OOPic-R microprocessor was utilized, giving each robot autonomous control over its electrical and communications devices. The small size of the OOPic-R was easy to integrate into the robot design. Three wireless communication protocols were available for transferring data between robots: Bluetooth, radio frequency and infrared communication schemes. During this initial development phase, Bluetooth was not available for purchase in the United States. Infrared was found to be the easiest and cheapest communication device. Infrared transmitters were placed on the stationary robot and the infrared receiver was placed on the mobile robot. Communication between these two components was only successful when the transmitter and receiver were in line of sight with one another.

The stationary robot housing consisted of three levels. The first level was for light sensing, the second level held the microprocessor and infrared communications, and the third level held the LCD display. It was quickly found that the LCD display drew too much power from the OOPic board. We decided that the LCD displays did not fit in the requirements of the design and were thus abandoned. The design of the light sensing level allowed the light sensor to rotate 90 degrees. The occurrence of the light spot on the table, or as a flashlight beam required the light sensor to point downward in the direction of the light source. Design and development of the stationary robot as a square shape seemed like a good place to begin (Figure 7). Testing demonstrated that the square shape of the second level had a direct impact on the light sensor's ability to determine the light spots' position. The second level cast a shadow over the first level and over the light sensor. The photo-resistor in the light sensing bred board was sensitive to environmental disturbances in light such as shadows. The basic, square shape of the robot served as a base geometry from which to cut away and modify sections as the robot as required.

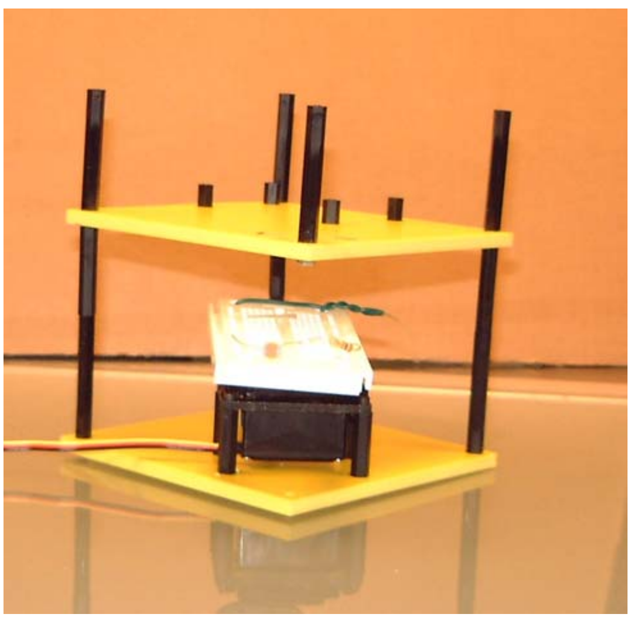


Figure 7: Team Spot Stationary Robot – First Prototype

The mobile robot was purchased in a kit from Lynxmotion (Figure 8) to jump start the development process. The kit insured that all the components of the mobile robot worked concurrently. Integration of the mobile robot with the stationary robots was more readily addressed.

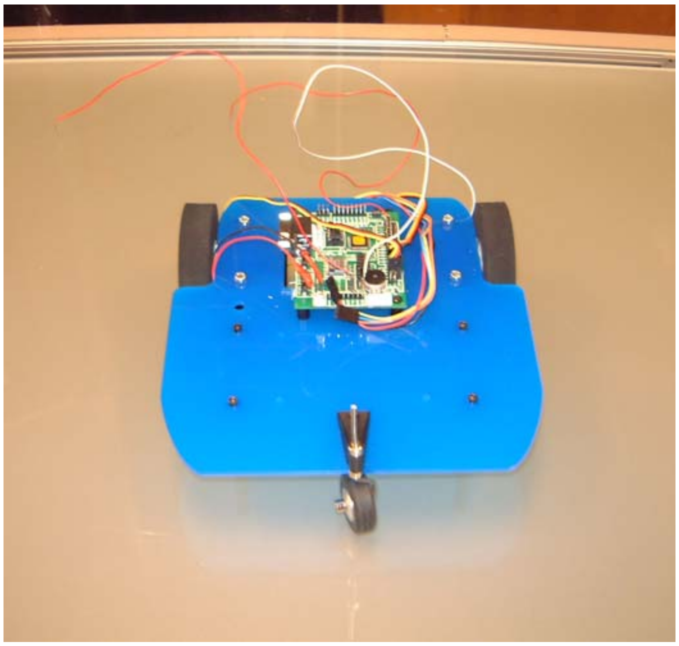


Figure 8: Team Spot Mobile Robot – First Prototype

Second Prototype

The designs of the first and second prototype were very different. A completely new communication protocol, Bluetooth, was used to transfer data between robots (Figure 9). The body designs of the mobile and stationary robots also received major design changes and took on a round shape. Issues that compromised the functionality of the first prototype were considered in the new design. The new design was tested and further modified in this stage of development.

Figure 9: Bluetooth Development Board (Wireless Futures, UK)

Robot Components:

- OOPic-R Microprocessor with Development Boards
- Bluetooth Communication Boards
- Photo-resistors (light sensors) with electronic breadboards
- Motors for rotation of light sensors (Stationary Robots Only)
- Motors for Mobility of Mobile Robot

The infrared communication used in the first prototype of Team Spot was sparsely accurate at best. Both the resolution of the angular position of the light spot, and the method of data transfer limited the mobile robot's ability to locate the light spot. Further research into the availability of Bluetooth development boards resulted in the purchase of a wireless cable from Wireless Futures, a Bluetooth development company located in the United Kingdom. Bluetooth is a wireless communication technology that transfers packets of data over short distances, usually 30 feet or less. Bluetooth works by sending data packets over a 2.4GHz radio-signal. It uses fast frequency hopping to avoid interference from other radio waves. Every Bluetooth device has a unique address, similar to an IP address. Using this address, Bluetooth devices are able to smartly send and receive data among one another. A Bluetooth device can be connected to as many as 18 other Bluetooth devices at a time. Using Bluetooth the light spot's actual angular position was transferred in a data packet. This eliminated the error of missed IR pulses that occurred in the first prototype.

The design of mobile and stationary robots consisted of two round levels (Figure 10, 11). The lower level housed light sensing components, while the upper level housed the OOPic-R and Bluetooth board. The lower level of the mobile robot also housed motors and wheels.

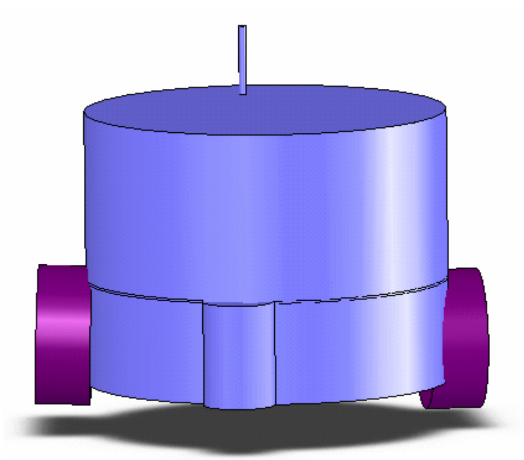


Figure 10: Team Spot Mobile Robot - Second Prototype

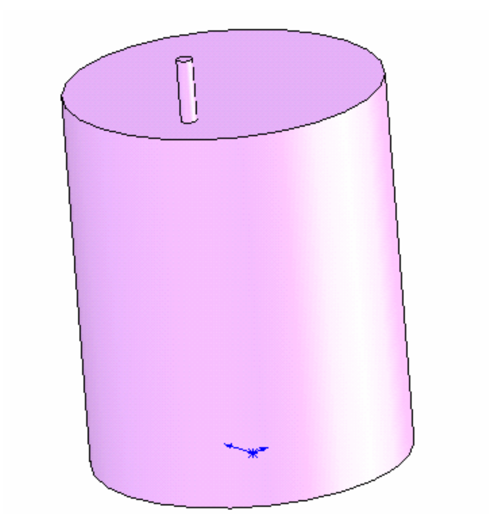


Figure 11: Team Spot Stationary Robot - Second Prototype

The second level of the stationary robot was changed to include a cut-out above the light sensor, thus preventing shadow interference. The modified design was then circular in shape with a half-moon cut-out above the light sensor (Figure 12). The cut-out allowed the light sensors to read the true light intensity at any light spot. A half moon shaped pop-out in the bottom level of the stationary robots pushed the light sensor out from below the second level of the robot, preventing disturbances in the intensity of incoming light. The combined effect of the first level pop-out and the second level cut-out was expected to solve the problem of shadow interference.

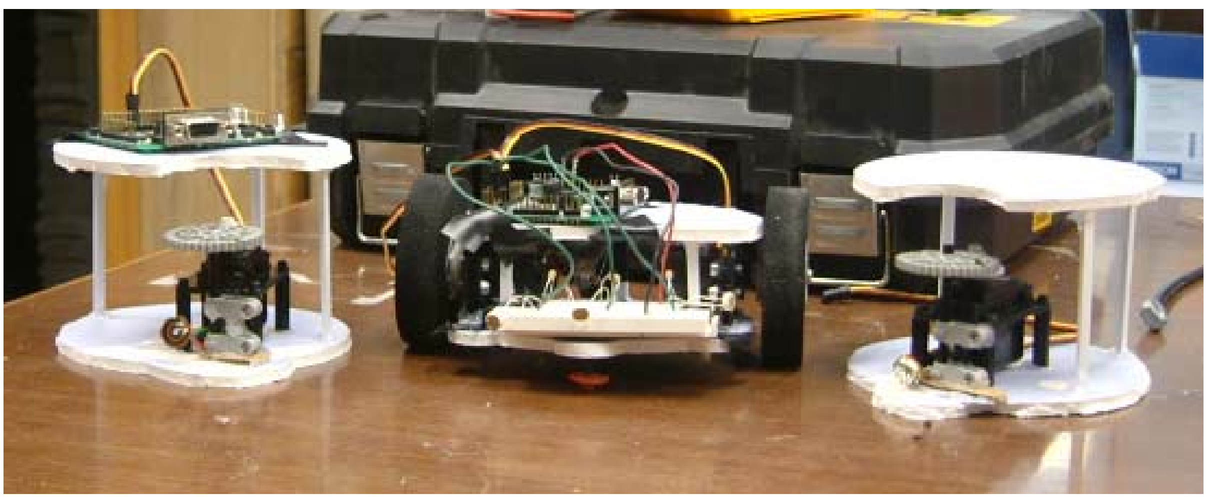


Figure 12: Team Spot - Modified Second Prototype

The motors on the stationary robot were geared down at a 5 to 2 ratio (16T to 40T). Servo-motors provided a ready-made internal gearing system, but for the purpose of scanning in search of the light spot, the motors moved too quickly. Lego gears, because of their ready availability, slowed the rotational speed by 80%. The light sensing circuit was attached to the top of the largest and outermost gear.

The design of the mobile robot was similar to the design of the stationary robot. The mobile robot had three light sensors, one pointing to the left, one to the right, and one pointing straight ahead. This configuration gave the mobile robot the ability to determine if it was on the correct path toward the light spot. If the mobile robot sensed a brighter spot of light, it changed course to head in the direction of greatest light intensity. The mobile robot's light sensor was wider than the stationary robot's light sensor and thus required a much larger cutout. One third of the mobile robot's second level was cut away to prevent shadow disturbances.

The base level of the mobile robot was round in shape, similar to the stationary robot. To accommodate the three light sensors, three half-circle shaped pop-outs were created in the front third of the base plate (Figure 12). Design variation between the mobile and stationary robots accommodated their differing light sensing schemes and allowed for light sensing with minimal disturbance.

This team of robots was constructed of foam-core poster board (Figure 12). This material is easy to use and modify, and allowed for fast development of the second prototype. Foam core's lack of durability and appearance made it a poor choice of ruse in the final robot team. A hot glue gun was used to fabricate the robots. Hot glue allowed for easy modification. Modifications to this design and Team Spot's performance was noted and used in the final robot design.

Final Robot Team

The final design was based on the successes and limitations of the second prototype. The design of the robots is similar, but differs to meet individual design requirements. All robots are circular in shape with cut-outs above the light sensors to prevent interference (Figure 13). The mobile robot has pop-outs for each light sensor and a larger cut-out on its second level. The stationary robot has small pop-out for its rotating light sensor and a half circle cut-out above the light sensor.

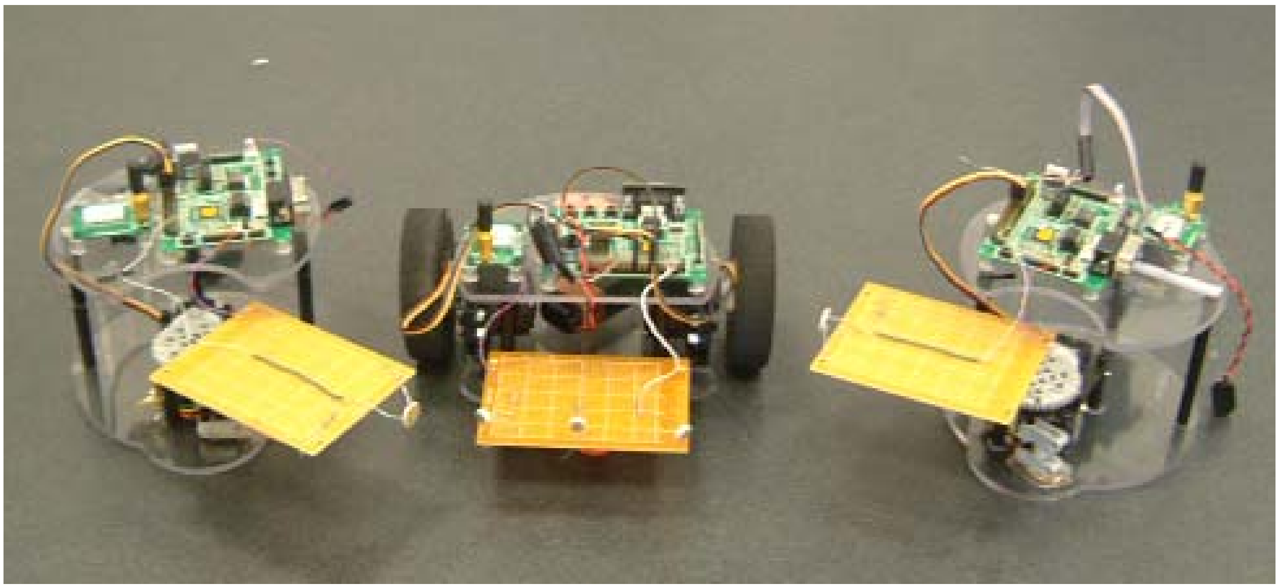


Figure 13: Team Spot – Final Design

The robots are fabricated out of 3/8 inch thick Lexan. Lexan is a strong and ductile plastic that comes in a variety of colors and thicknesses. It is popular for its appearance, good material properties, and easy machinability. Clear Lexan was chosen over PVC and acrylic for these reasons. Unlike the PVC used in the first prototype, the clear Lexan was easily and cleanly machined. The Lexan did not compress under the stress of screws, and its clear nature of the Lexan allows the inner components of the robots to be viewed by observers. Team Spot utilizes only the base and mid-plates to allow the microprocessor and communications equipment to be easily accessed in the final stages of robot testing and calibration.

Testing and Results

Testing occurred in several settings: the ROBOTable; a 3x2.5 foot area on a concrete floor; and a completely dark 3x2.5 foot area (the TUFTL sound room). The robots were most successful finding the light spot in the TUFTL sound room, due to the lack of interfering environmental light. For this reason, Team Spot's communications and light finding algorithms were tested in the TUFTL sound room. In a series of 12 trials Team Spot's communications were successful 91% of the time and the algorithms were successful 83% of the time.

In the development of the first and second prototypes the functionality of the robot body design was tested. The resulting modifications increased Team Spot's light finding ability. The final prototype was tested for functionality in communications, algorithm and path of travel.

Team Spot's first and second prototypes were tested in two situations: the ROBOTable with the light spot as a white circle projected onto the tabletop screen and a darkened, windowless room. The primary design constraint is that the robots work effectively on the ROBOTable. As a result of environmental noise from other computer screens and windows in the room, all prototypes and the final team were unable operate on the ROBOTable. Testing of the team's effectiveness occurred in a darkened, windowless setting with a flashlight providing the light spot.

The body dimensions and appearance of Team Spot were designed to integrate effectively with the table. The size of the robots was kept small: 5 inches in diameter and less than 6 inches in height. The robots were designed for easy placement on and removal from the ROBOTable. The mobile robot was small enough to maneuver around the table. Set-up and removable of Team Spot was easy.

To eliminate environmental lighting the robots were tested in the Robotics Academy laboratory space with the lights off and main door closed. A flashlight provided the light spot. This setting was beneficial because it lacked interfering light from computer screens and windows. Team Spot demonstrated improved accuracy in locating the light spot, but still suffered from streams of light coming in under the laboratory door. In an attempt to completely eliminate interfering light, Team Spot was moved to the TUFTL sound room for testing. The sound room is without windows or computers and its floor, ceiling, and walls are covered with dark foam and carpet. With the door closed and the overhead light off, the sound room was a perfect test setting.

Testing in the TUFTL sound room was successful. The stationary robots accurately located the light spot coordinates, sent the information to the mobile robot, and the mobile robot was able to travel to the light spot and follow it as it moved. Although the final testing arena was outside the problem constraints, it provided the ideal setting for actual testing of all system components.

Analysis of Results

Team Spot was successful in locating the light spot, but only in a very controlled setting. On the ROBOTable (with the table computer monitors on, room lights on, window shades up, and other computer monitors in the room on (Figure 1) Team Spot was unable to distinguish between the light spot projected onto the surface of the ROBOTable and other bright sources of light in the room. Modifications to the test setting provided Team Spot with an ideal (dark) space in which to operate. Only in a space void of all light, except the bright light spot, was Team Spot able to find the correct light spot coordinates. Although other problems hampered Team Spot's success, its inability to successfully operate on the ROBOTable was the largest digression from the original problem constraints.

Other problems plaguing the robots' light finding ability include the infrared and Bluetooth communication devices, the motors driving the mobile robots' wheels and the precision of the PIC sine function for some placements of the light spot.

Team Spot's ability to connect and communicate during every attempt is a reoccurring problem. The infrared communication boards are plagued with problems. The infrared transmitter and receiver required line-of-sight placement to best transfer data. Although some data was transferred through diffuse infrared signals, the best data transfer occurred when the transmitter and receiver could see each other.

The stationary robots transfer the angular position of the light spot to the mobile robot by sending IR pulses. The number of pulses sent corresponds to one of seven angular positions of the light spot. The mobile robot uses a look-up table to convert the two numbers of pulses into x and y coordinates of the light spot. However, the IR receiver on the mobile robot often missed pulses from the stationary robots, destroying the PICs ability to accurately determine the x and y coordinates of travel.

In the first prototype, the mechanical design of the stationary robots' top (third) level was believed to be obstructing IR travel. It was modified by removing support posts and the top level. This seemed to have little effect on Team Spot's ability to communicate. As testing of the first prototype was completed, it was determined that IR communication was intermittent at best and that Team Spot's wireless communications system must be replaced.

The second prototype employed a Bluetooth wireless cable to transmit data. The Bluetooth boards transmit much more data than the IR circuits, allowing the angular positions of the light spot to be transmitted to the mobile robot. The mobile robot uses the PIC sine function to calculate its x and y coordinates of travel. This method provides greater accuracy than the first prototype's look-up table. Although the Bluetooth devices were able to transfer data in packets, they showed trouble connecting with each other, sometimes failing multiple times in succession. A programming scheme optimizing the order and method in which the devices connected improved their ability to connect and transfer data. The functionality of the Bluetooth did not depend on the mechanical design of either the stationary or mobile robots.

The mobile robot is driven by HiTech HC-422 servo-motors. The power of these motors is uneven, causing the robot to veer off its intended path. One wheel, robot left, consistently drifts to the right. The motors were swapped for new motors, but the problem continues to occur. After some testing, the potentiometer was placed back inside the motor housing. It had been removed from the motor casing while modifying the motors. This change yielded considerable improvement in the robot's ability to drive straight, but the robot remains far from perfect. The cause is due to either a mismatching of equal strength motors, or an inherent problem in the PIC programming or data output lines. In further development of Team Spot, stepper motors will replace the HC-422 motors.

When the light spot is placed in particular distant positions, the stationary robots register a position measurement that causes the PIC's sine function to tell the mobile robot to drive an indefinite distance. In testing and demonstration of Team Spot this phenomenon was observed on multiple occasions. In further development, a safe guard will be programmed into the mobile robot, telling it to recalculate the light spots coordinates or to request new position data from the stationary robots.

Despite the problems and limited success encountered in testing, the mechanical design and the design and development of the robot is considered partially successful. A design and development process was followed from project conception through the final product, with each phase of development building on the success and failures of the previous stage. The mobile and stationary robots' mechanical design met the design objectives. Both designs were compact and effectively housed the light sensing, communications, and computer processing equipment. Neither design limited functionality. The mobile robot's gearing system slowed the light sensor rotation, matching the sampling rate of the PIC data line to angular positions in the light sensor rotation. Failure in the mobile robot's driving motors was an unsuccessful component in mechanical development. Even when the communications and algorithm were successful, failure in the mobile robot's driving prevented the team from locating the light spot.

In terms of algorithmic functionality, Team Spot demonstrates the effectiveness of autonomous robot teams. This algorithm distributes light finding between the stationary robots and then transfers the light spot's angular positions to the mobile robot. The mobile robot uses the light spot's angular positions to map a path of travel. Team Spot's algorithm located the light spot 83% of the time.

Team Spot also demonstrates a novel use of Bluetooth. The Bluetooth master and slave devices must first establish a connection to transfer data. After data transfer the devices sometimes remain connected and other times they disconnected. Another master device could not connect to the slave device while it remained connected to its current master. The process of connecting and disconnecting was time consuming. Failure to connect or a loss of connection between Bluetooth devices required that the data transfer process be repeated from the beginning. Bluetooth communications were successful 91% of the time.

CHAPTER IV

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

The development of Team Spot tests the abilities of a robot team designed to locate a target. The combination of robot types (mobile and stationary) demonstrates that, similar to teams of humans that collaborate to effectively solve problems, a robot team consisting of robots with various specializations has enhanced problem solving capabilities.

Likewise, the multi-discipline nature of the design team led to a highly effective, collaborative design process. Each team member represented a unique engineering specialization, yet was able to design components that integrated well with those designed by other team members. This collaborative process demonstrates the benefits of a multi-discipline design team working together during each phase of a project. The team process allows each member to become familiar with the other aspects of design, thus taking the size and function of all components into consideration when completing specialized design tasks.

Team Spot was developed in a series of stages, resulting in a working team that consisted of two stationary and one mobile robot. The team was designed to locate a light spot on a ROBOTable and communicate the coordinates of the light spot target. Testing on the ROBOTable was unsuccessful because of environmental light that interfered with the light sensors. The team was tested in two other locations. Team Spot performed successfully when tested in a darkened room.

Conclusion

Team Spot uses two stationary and one mobile robot to determine target coordinates and travel to the actual location of a target. The initial target of a light spot on the ROBOTable proved problematic in testing. A completely darkened room provides the best environment for testing Team Spot.

Team Spot's communication via Bluetooth is of novel use in the field of robotics where most wireless communication is via infrared (IR) or radio-frequency (RF). Team Spot's ability to decide which robot to communicate with gave them the power to provide specific information to each other. Bluetooth's data-exchanging base increased Team Spot's problem-solving ability. The detailed information communicated via Bluetooth allows the mobile robot to calculate an accurate path of travel to the target. This was not possible to communicate with IR communication.

The problems successfully solved throughout Team Spot's design and testing process offer valuable information about interactive autonomous robotic teams seeking a common target. Team Spot's functionality demonstrates how robot teams can successfully communicate and collaborate. Team Spot's collaborative process further demonstrates how robotic teams may identify and solve problems effectively and efficiently by multitasking according to team member specialization

Recommendations

A team of mobile, autonomous robots was developed that locate and travel to a target. The team of robots is comprised of one mobile and two stationary robots which communicate light position data via Bluetooth chips. Each robot is completely autonomous. If the mobile robot receives data from the stationary robots that leads it to an incorrect position, it has the autonomous capability to begin searching for or following the light spot.

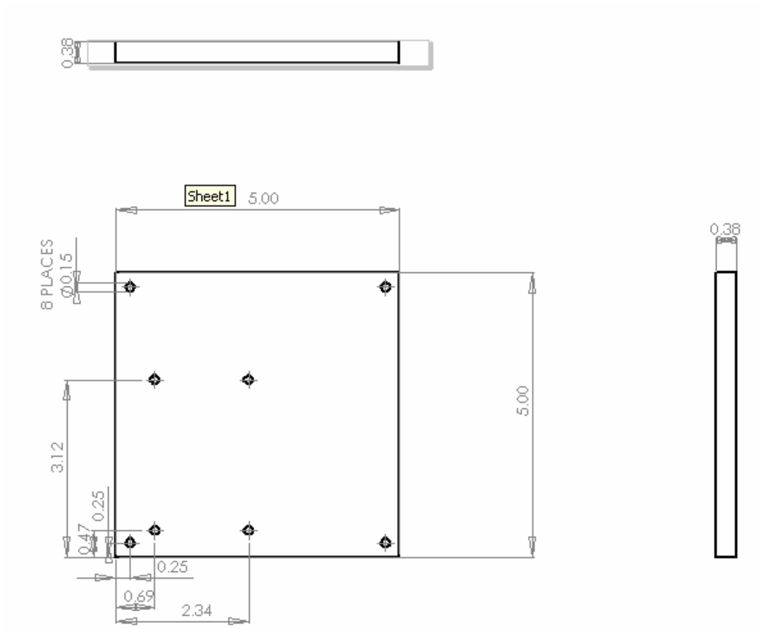
Development of Team Spot was a multi-discipline effort. All aspects of design, building, and testing required input from electrical, mechanical, and computer engineer team members. This collaborative problem-solving environment enhanced the development of Team Spot's functionality. Effective robot design and construction is truly a multi-discipline field.

Team Spot may be modified for future use and display. The servomotors may be replaced with stepper motors to allow the mobile robot to travel in a more linear path. The target may be altered to something less temperamental than light. Possible solutions discussed have included using sonar detectors to locate three-dimensional objects or infrared detectors that locate an infrared source. Significant research has gone into modifying the robots with sonar detectors.

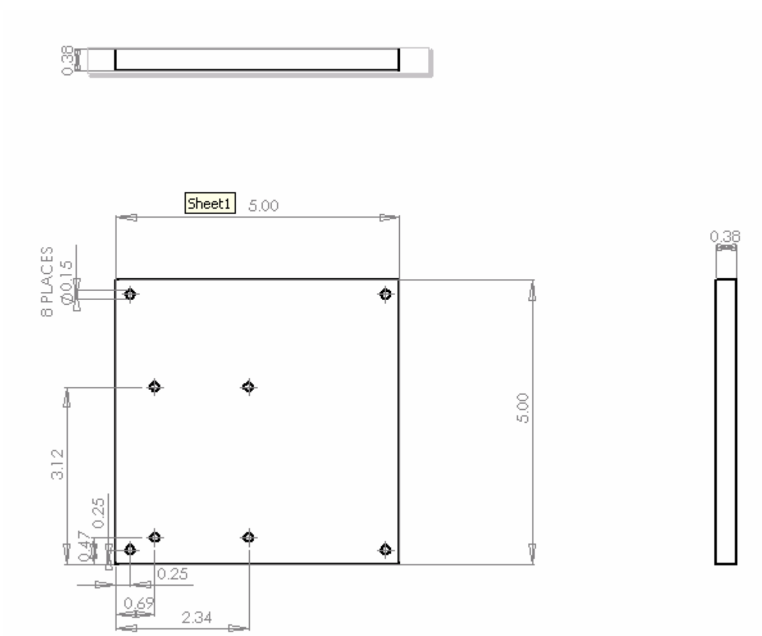
The problems Team Spot encountered in detecting the light spot are significant. Further development of target finding robot teams will likely undergo the same problem. Chemical sensing robots will have to be programmed to overcome naturally occurring odors or toxins, which may confuse them as attempt to locate a target. Clearly, much work is required in development of sensing components.

The development of teams of mobile autonomous robots is an exciting and expanding field. Team Spot demonstrates the efficacy of such a team. The research contained in this project can provide a good starting point for another design team building an autonomous mobile robot team.

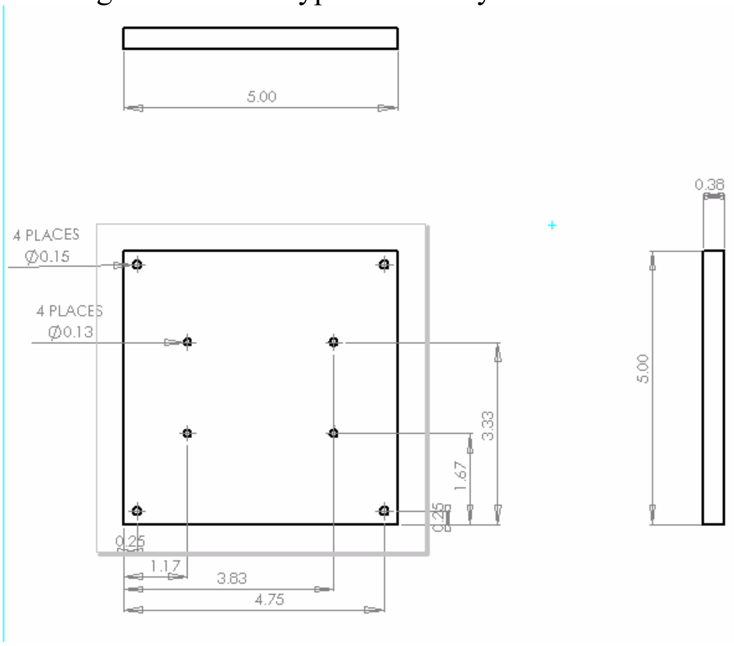
Appendix A: Robot Drawings



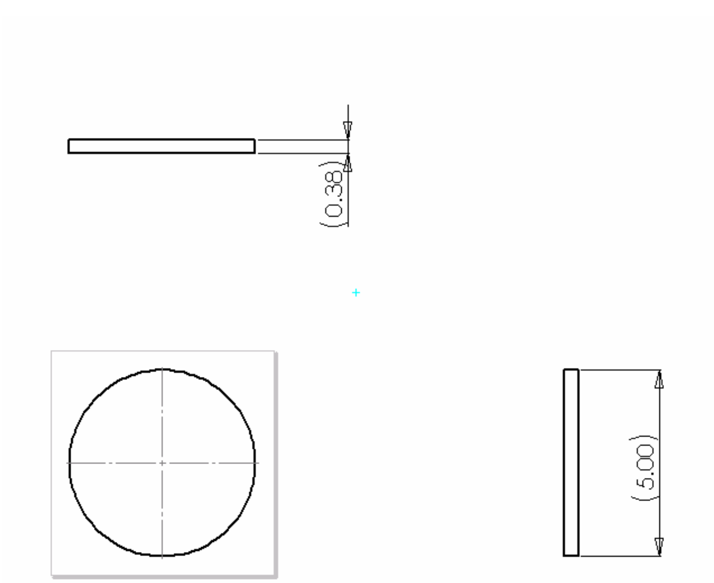
Drawing 1: First Prototype: Stationary Robot Base Plate



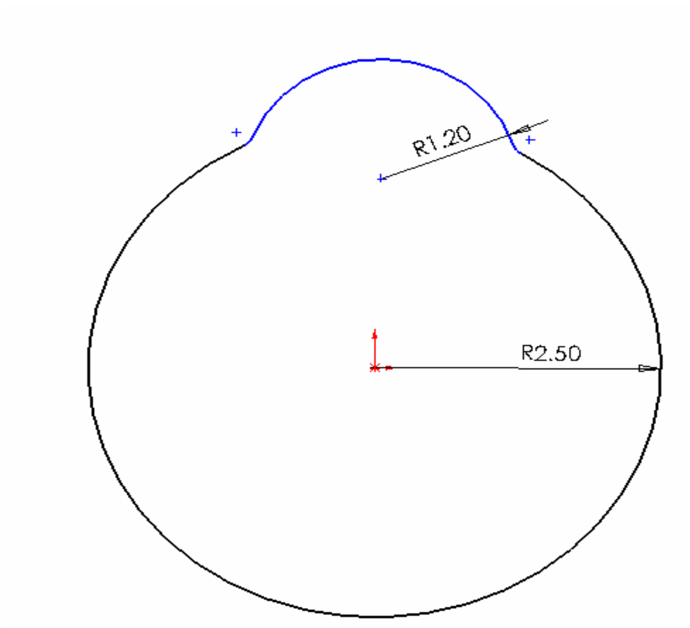
Drawing 2: First Prototype: Stationary Robot Mid Plate



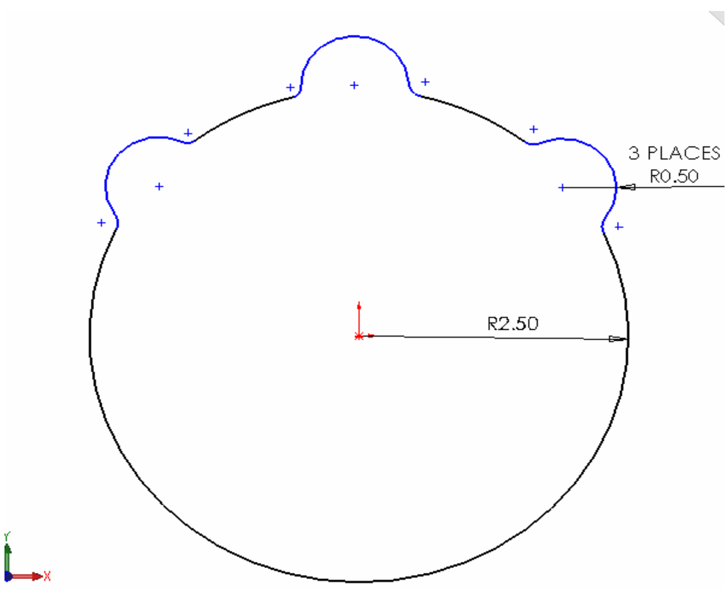
Drawing 3: First Prototype: Stationary Robot Top Plate



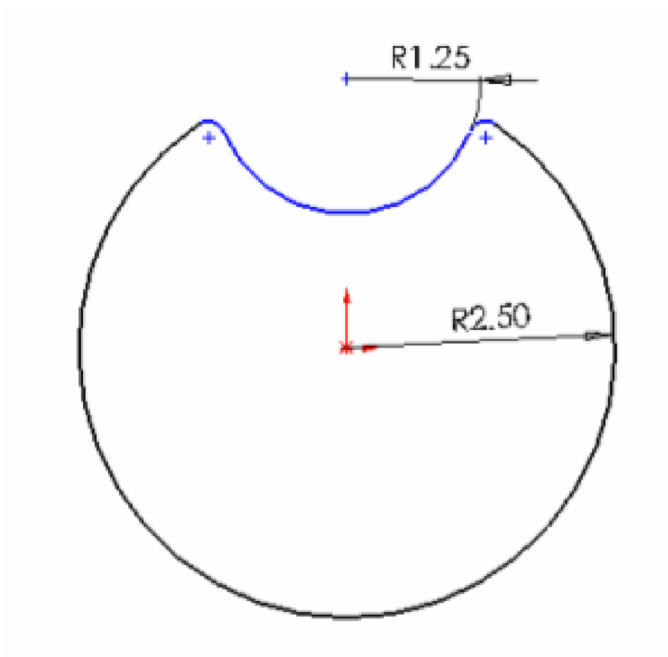
Drawing 4: Second Prototype - Base, Mid and Top Plate for Mobile and Stationary Robot



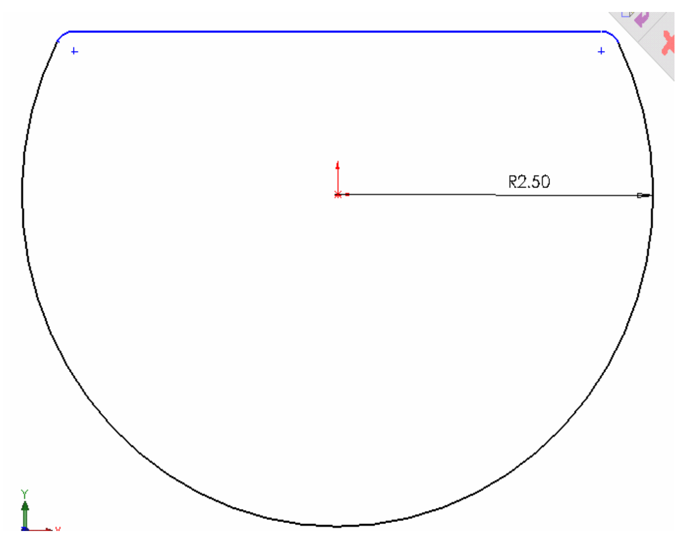
Drawing 5: Final Design - Base Plate for Mobile Robot



Drawing 6: Final Design – Stationary Robot Base Plate



Drawing 7: Final Design –Mid Plate for Stationary Robot



Drawing 8: Final Design – Mobile Robot Mid Plate

Appendix B: Definition of Terms

Augmented Reality	The overlay of virtual world objects in a real word setting. The ROBOTable employs augmented reality.
Autonomous Robot	A robot that processes information independent from a mother processor.
Bluetooth	A specification for short-range radio links between mobile devices.
Breadboard	A board with lots of small holes, linked with conductive traces in rows that is used to prototype electrical devices.
CNC	A computer controlled milling machine.
ROBOTable	An augmented reality table, that promotes collaboration of robot building and testing in an interactive distance learning environment.
Infrared (IR)	A communications method in which data is sent at an infrared frequency.

Lexan	A trade name for a polycarbonate sheet. It was used in final fabrication of Team Spot.
MicroController	A single-chip microcomputer with on-board program ROM and I/O that can be programmed for various control functions
Mobile Robot	A robot that can travel throughout its environment.
Photoresistor	An electrical device whose resistance decreases with increasing incident light intensity.
PVC	Polyvinyl Chloride. A commonly used inexpensive plastic that is easy to cut and assemble.
ROBOlab Software	Pictorial programming language designed for students to program the Lego RCX brick.
Robot Team	Several robots that work together to solve a problem or complete a task.
Servomotor	A motor is that controlled by an amplified signal from a command device of low power, as in a servomechanism.

Solid Works	A mechanical engineering design program used to create two dimensional drawings of mechanical parts, as well as three dimensional solid models of parts.
Stationary Robot	A robot that performs its functions without changing its location or moving through space.
TUFTL	Tufts University Future Technologies Laboratory – Home of the Robotics Academy and the ROBOTable.

Appendix D:
Robotics Academy-Team RoboSpot Proposal

Problem:

To develop a team on mobile autonomous robots that, within a fixed boundary, can locate a spot of light on the HITable. The robots are expected to converge on the spot of light and report its coordinates. The experiment will take place on a HITable (human interface technology table), which operated in augmented reality, enabling users in different locations (e.g. Tufts University and New Zealand) to interact with each other and with each other's robots. A projector beneath the table projects a computer-generated image up onto the frosted glass surface. The robotic team will interact with this projected image in real time. The table will allow for an upward diffusion of light that the robot's light sensors can detect. The area of the table not occupied by the spot(s) of light will be black.

The first component of the problem is to determine the location of a single spot of light on the table. The single spot problem has been chosen for its relevance to the real world problem on which this experiment is based. Only one area on the table will be lit at any time during execution. As previously stated, all areas around the light spot will be black and without a gradient of light. The goal of this component will beto locate, converge on, and report back the relative coordinates of the center of the spot of light. The simplicity of the single spot problem (versus a multiple or growing spot problem) has also led to its selection as the component first addressed. The single spot problem is easier to program onto the table, which is also in the intial stages of development.

The growing spot component is directly proportional to the single spot component. The light will originate at a single spot on the table, and will begin to expand outwards at a constant rate, creating a gradient of light. The light will not expand beyond the boundaries of the table and will advance in a concentric manner from the center of the spot. The robots will be expected to locate the light gradient, follow it to the center source and then report back the relative coordinates at the center.

The multiple spot component is also a continuation of the single spot component. In this component, several single spots of light will be illuminated at various points on the surface of the table. Once again, the areas of the table not lit up will be black. The robots will prioritize the light spots by the measured intensity of the spots. The mobile robots will be sent to the center of each light source in order of the priorities determined by the robots. If there are more light spots than robots, the robots will arrive at the spots of greater luminosity, transmit the coordinates, and then advance to the remaining centers of light.

To further advance the problems, the boundaries of the table can be altered to fit with an educational or interesting story. Walls can be shown on the table as areas void of light and would thus be areas that the light cannot diffuse through and the robots could not travel though. This situation would simulate the real world problem upon which this project was created.

Design Constraints:

The constraints placed on this problem are related to the robots themselves and the environment in which they operate. Though the eventual goal of this project is to design robots that can work in any environment, the robots will initially be limited to the ROBOTable. The physical extents of the search are the *two-foot by three foot* table area and the table's unprotected sides. Furthermore, by using the RoboTable, the light spot can be closely controlled. Initially, the robots will only search for a single light spot.

In choosing a small space for the robots to search, the robots themselves must be sufficiently small so that they do not take up a large amount of the table. Small robots will also limit the number of collisions if multiple robots are used.

Though the use of light sensors to find a spot of light might seem like an obvious choice, the team has chosen to reject solutions which do not use light sensing technology, as applicability to the real world is a major concern.

The robots must be autonomous and not use a central processing unit to send and receive commands. This constraint was added to be responsive to the original idea of searching for Cyanide in subways. Ideally, a system for search and rescue will be resilient to attacks on the system itself. In an attack situation, a team of robots directed by a central computer is disabled if the central computer is attacked. Therefore, this team has decided to design interconnected robots with the ability to function if one or more is disabled. These robots must each have an embedded microchip.

The final constraint placed on the robots is that they must be able to communicate with one another and work collaboratively to find the light spot. A simple solution to this problem would be to have robots comb an area and stop once they found the light. However, in order to keep the original goal of this project in mind, solutions in which the robots do not communicate have been rejected as outside the scope of the problem.

Educational Application:

A light-seeking robot project could augment several types of lessons in the elementary or middle school classroom, including: geometry and graphing, working with data, problem-solving strategy, and, in older classes, physics.

Within geometry, our solution addresses: points, lines, angles, and right triangles. From the related domain of graphing, it employs: the x-y coordinate system, plotting, line intersection, slope of lines, x and y components of lines, and graphing to solve a problem.

The project also teaches children how to work with data: collecting it (angle, time, and luminosity measures) and analyzing it (finding the peak value of luminosity).

More generally, the initial statement of our task (or a simplified version) could be assigned to teach problem solving strategies such as: simplify the problem, break it into smaller parts, brainstorm ideas, test them out/check if the answer makes sense, and find limitations of the solution and ways to improve it. The project could lead to written word problems testing math skills or to experiential problems requiring direct work with the Robotable, thus asking children to solve both abstract and concrete problems.

Finally, older children could learn about some of the physics/technology that makes the Robotable possible: "distance = rate * time" or properties of light and IR waves that allow the robots to communicate.

The Robotable contextualizes these potentially isolated math, science, and technology topics, making them more relevant and interesting to learn. When children are invested in a "real-life" project that uses information and skills they learn in school, they are more likely to stay engaged, enthusiastic, and expand their thinking.

Diagrams of Possible Robot Systems (Single Light Spot):

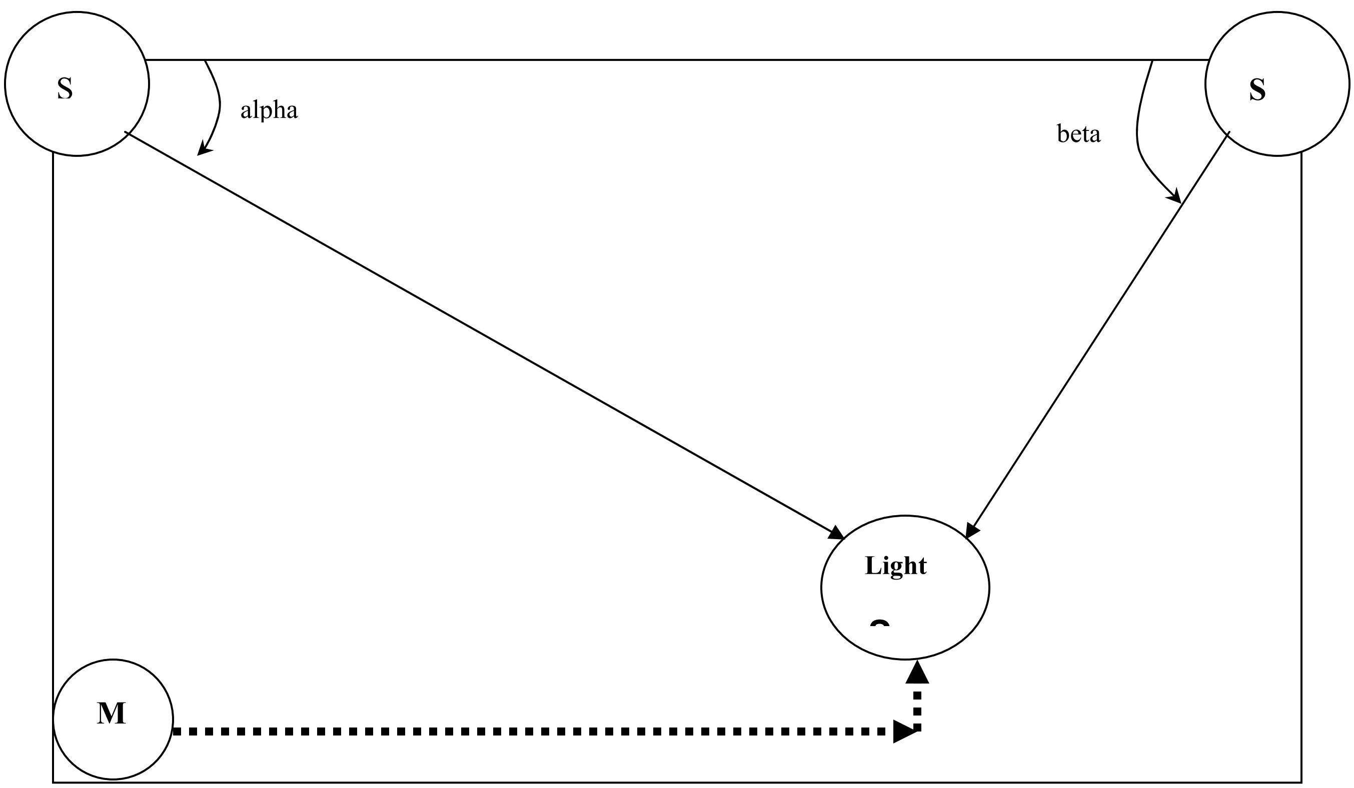
1) 3 Robots (2 stationary; 1 mobile)

-The two stationary robots will scan 90 degrees and determine the angle with the greatest light intensity.

-The stationary robots will send this angle to the mobile robot and the mobile robot will determine the coordinates of the light source and travel to it.

-As the mobile gets closer they will search for the direction of greatest light to secure that they are headed for the light spo.

-Once the mobile robot has located light spot it will report its location to the stationary robots.



2) 3 Robots (2 robotic arms; 1 mobile robot)

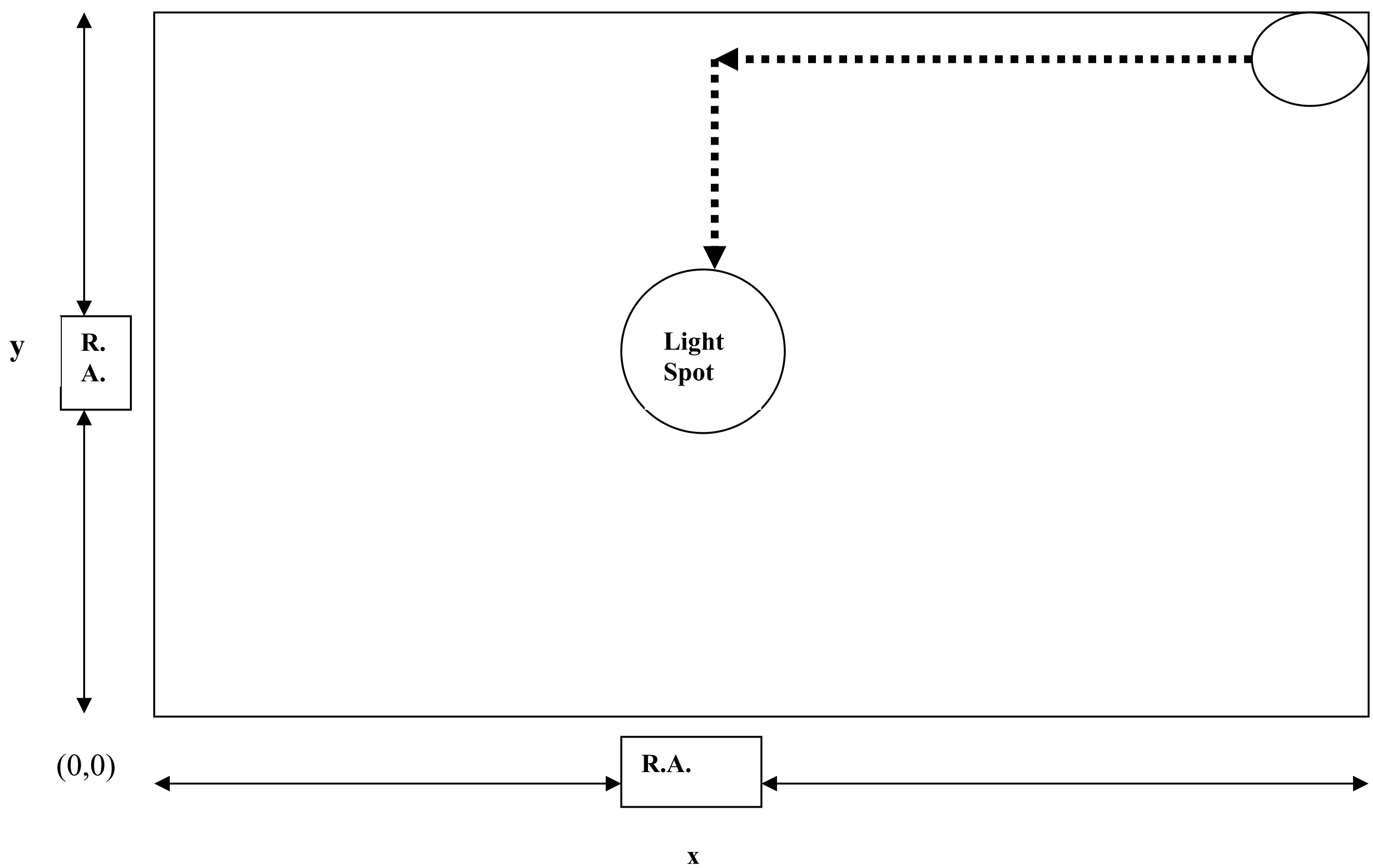
-Robotic arms locate the x and y coordinates with the greatest light intensity and send the information to the mobile robot.

-The mobile robot processes this information and travels to those x and y coordinates.

-One at the x and y coordinates, the mobile robot checks that a greater light intensity doesn't exist in another direction.

-The mobile robot decides if it should move to a new location or if it has located the light spot.

-When the mobile robot has found the light spot it reports its coordinates.



3) 4 Mobile Robot System

-Quadrant system

-Simplistic robot behavior

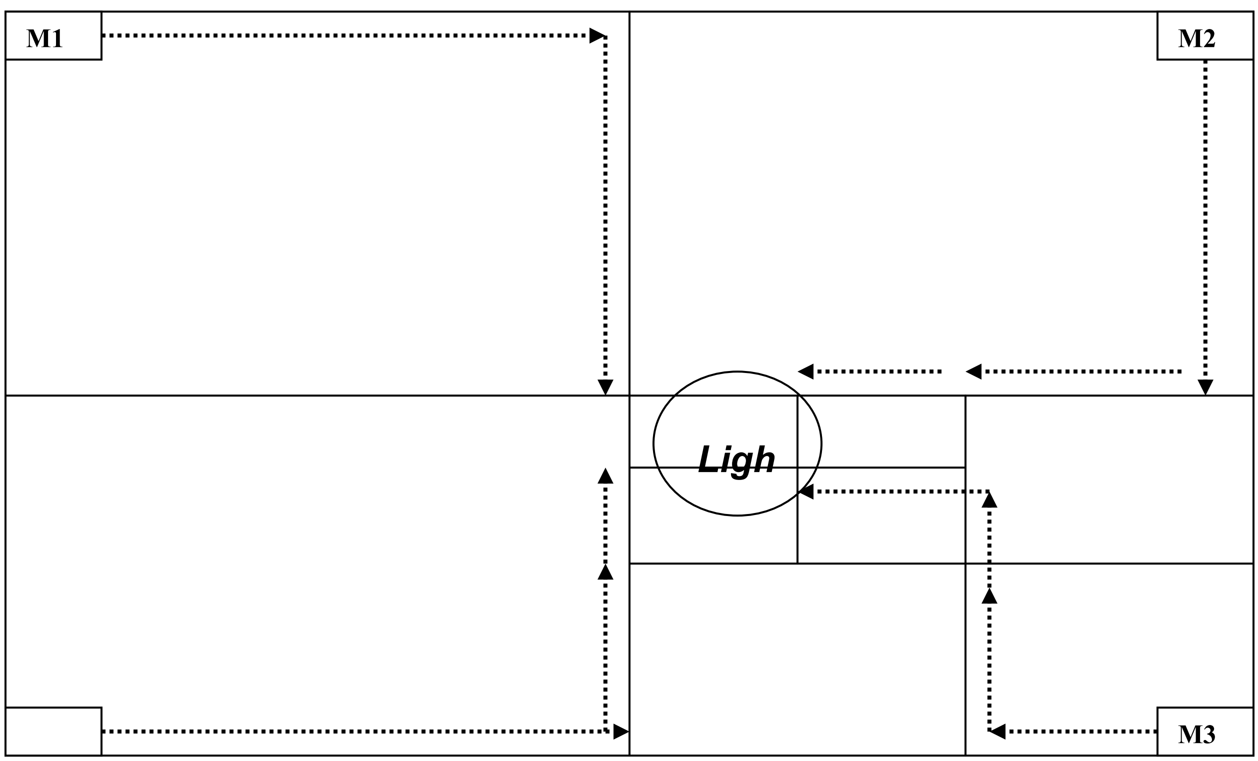
-More time consuming

-The mobile robots will determine which quadrant has the light spot it in and then subdivide that quadrant into 4 quadrants.

-The mobile robots will move to the corner of their new sub quadrants and decide which sub quadrant has the light spot.

-The mobile robots will repeat the process until they converge on the light spot.

-When the mobile robots have found the light spot they will report its coordinates.



Appendix G:
Team Spot Budget

Team Spot Budget			
Category	Budgeted	Spent	Difference
Light Sensing	$50.00	$10.33	$39.67
LCD Panels	$200.00	$147.00	$53.00
IR Communication	$50.00	$61.80	($11.80)
Bluetooth	$800.00	$630.00	$170.00
OOPICs (6)	$500.00	$427.72	$72.28
Robot Body Material	$100.00	$64.57	$35.43
Robot Motors	$100.00	$90.00	$10.00
Mobile Robot Kit	$300.00	$319.83	($19.83)
Misc. Hardware and Electonics	$500.00	$363.83	$136.17
Books	$100.00	$82.38	$17.62
Totals	$2,700.00	$2,115.08	$502.54

Part Description	Manufacturer/Supplier	Part Number	Number Required	Cost
Light Sensing				
Photo-resistors (mixed pack)	Radio Shack	2761657	2	$5.38
Optical Sensor	Budget Robotics	SENS200	3	$4.95
Communication				
IR Remote	Reynolds Electronics	TX-IRHS	4	$32.00
IR Module	Reynolds Electronics	TSOP7000	4	$18.00
IR LED	Reynolds Electronics	TSHF5400	4	$5.40
Ceramic Resonator	Reynolds Electronics	20MHz-CERAMIC	4	$6.40
BlueWAVE Kit	Wireless Futures	n/a	1	$400.00
Bluetooth Communication DTCE	Wireless Futures	n/a	1	$200.00
Bluetooth Dongle	Wireless Futures	n/a	1	$30.00

Microprocessor				
OOPIC-R	Lynxmotion	00P-01	5	$399.75
Serial Cables	Lynxmotion	DB9-02	2	$19.90
OOPIC-R Programming Manual	Amazon	71420843	1	$27.97
Mircocontroller Projects Book	Amazon	1578201012	1	$33.44
Robot Building for Beginners	Amazon	1893115445	1	$20.97
Misc Electronics and Other Stuff				
LCD Panels	Lynxmotion	SLM-01	3	$147.00
Wiring Kit	Radio Shack	2760173	1	$5.99
9V Batteries	Radio Shack	2300883	1	$9.99
AA Batteries	Radio Shack	2300874	3	$20.37
9V Batteries	Target	57060184	2	$15.98
AA Batteries	Target	57060291	1	$4.69
Battery Packs	Lynxmotion	BH-03	4	$4.00
Wire Stipper	Radio Shack	6402129	1	$2.99
Serial Socket	Radio Shack	2760175	3	$23.97
Octal FF	Radio Shack	2762881	3	$3.87
D-Sub Male	Radio Shack	2761427	3	$4.47
Comparator	Mouser Elect.	512-LM2901N	10	$3.60
Flip-Flops	Mouser Elect.	512-74ABT273CSC	10	$5.80
Transistors	Digi-Key	ZTX603-ND	10	$8.15
Body				
Mobile Robot Kit	Lynxmotion	CROC-KT	1	$259.88
Servo Board	Lynxmotion	SSC-12	1	$59.95
Yellow PVC	Budget Robotics	PVC-1212	4	$15.80
Pan and Tilt Kit	Lynxmotion	APT-KT	2	$90.00
1/4 4-40 Steel S/H	Lynxmotion	SHS-01	1 bag	$4.35
1/2 4-40 Steel S/H screws	Lynxmotion	SHS-04	1 bag	$5.35
3/8 4-40 Steel S/H	Lynxmotion	SHS-02	1 bag	$4.85
3/8 4-40 Steel S/H screws	Lynxmotion	BHS-01	1 bag	$4.85
1/4 4-40 Steel Nuts	Lynxmotion	SN-01	1 bag	$2.95
2x1/4 Nylon MF Hex SO	Lynxmotion	NHS-12	2 bags	$11.50
1.5*1/4 FF Nylon Hex SO	Lynxmotion	NHS-04	2 bags	$11.50
1/8x1/4 FF Nylon Hex SO	Lynxmotion	NHS-01	1 bag	$4.85
Poster Board	Playtime	n/a	1	$1.99
Plastic Strips	Playtime	n/a	1 bag	$4.99
Lexan Sheets	Playtime	n/a	4	$39.80
Flexible Polyester Plastic Backing	Playtime	n/a	1	$1.99
Misc. Supplies				
Glue Gun	Playtime	n/a	1	$2.99

Hot Glue	Playtime	n/a	1	$0.99
Exacto Knife	Playtime	n/a	1	$4.99
Sharpie Markers	Playtime	n/a	2	$3.98
Glow in the Dark Stickers	Playtime	n/a	2	$2.58
Super Glue	Target	85040168	1	$2.49
Epoxy	Target	85041220	1	$2.99
Sodder	Hillside Hardware	n/a	1	$1.59
Light Bulbs	Target	85020405	1	$1.04
Tension Cord	Target	68050280	1	$6.99
Night Lights	Target	80571692	1	$3.99
Night Lights	Target	85071804	1	$4.99
Night Lights	Target	85071819	1	$2.99
Mounting Tape	Target	81060046	1	$1.99
Extension Cord	Target	85071923	1	$1.99
Tape	Playtime	n/a	1	$1.35
Isopropyl Alcohol	Target	94070174	1	$0.84
Exacto Knife	Target	85050013	1	$3.99

Appendix H:
Team Spot Addendum to the Budget

Part Description	Manufacturer/Supplier	Part Number	Number Required	Cost
Stepper Motor - Large	Alltronics		2	$19.90
Stepper Motor - Small	Acroname		2	$9.90
Sonar Ultrasonic Ranger	Acroname		2	$34.50
Total				$64.30

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The Official Bluetooth website [Online] http://www.bluetooth.com

Wireless Futures Official Website [Online] http://www.wirelessfutures.co.uk