WORCESTER POLYTECHNIC INSTITUTE

ROBOTICS ENGINEERING PROGRAM

Final Project

SUBMITTED BY

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Date Completed	**: [Date of the lab]**
Course Instructor	**: Prof. Putnam**
Lab Section	**: C01**

Contents

Section 1: Introduction

According to the National Fire Protection Agency, there was an estimated 365,500 fires reported in 2015 [4]. While this is less than the reported 381,000 fires of 2005 [4], a significant number of deaths and injuries occur due to cooking and heating equipment left unattended [3]. To combat this, some system capable of autonomous monitoring and extinguishing of small fires must be implemented into the common American household. Such an autonomous system would function in a similar way to the iRobot Roomba- with regards to its independence, navigation, and overall functionality- except it would focus on extinguishing or delaying the spread of small fires rather than the cleanliness of a room.

To simulate this task, the RBE 2002 term project is designed around the idea of a robot fighting a fire in an unknown environment. As is the case with real incidents, the fire may not always be immediately visible from the starting location of the robot. Therefore, a firefighting robot must be able to autonomously locate, navigate to and extinguish the fire with minimal human interaction. If possible, the robot should be able to return to its original starting position, similar to the most current model of Roomba vacuums. Additionally, it is necessary for such a robot to announce in some way that the fire has been located, and subsequently extinguished, as well as the location of the fire in relation to the robot's starting point, such that the homeowners could know when they must leave, if it is safe to enter, and where the fire originated. [5]

In the case of the aforementioned term project, the majority of the requirements for a proper firefighting robot experience a reduction in some form. With the term project, the fire to be extinguished is a candle between 10 and 30 centimeters, instead of an outlet or appliance on fire. In lieu of an entire household, a square field eight feet to a side was used to test the robot's ability to accomplish the task at hand. Considering that most appropriate forms of household fire extinguishers utilize a condensed form of fire-fighting gas, such as CO_2, or a foam of some sort, which can either be deadly or messy in large amounts [1], and the field would be used by multiple teams, robot designs were encouraged to find other solutions to extinguishing the flame. Additionally, teams were not given an abundant amount of time to complete the task. Since a full scale fire can become life-threatening in as little as two minutes and engulf an entire residence in as little as five [2], teams were allotted only five total minutes to locate and extinguish the flame. [5]

Section 2: Methodology

From the details laid out in the introduction above, several key aspects of an appropriate robot would need to be implemented. First and foremost, a method of navigating reliably and safely around the field was needed for the robot. Next, a solution to extinguishing the flame needed to be finalized. Following these two requirements, the necessary sensors and subsequent state programming were developed in order to complete the robot. With these four main components finalized, the robot was able to complete the task at hand.

2.1 | Structure

Bearing in mind that a size limit was imposed on all teams, such that a team's robot could be no bigger than a box 12.5 inches to a measurable length or width, space was limited for the task at hand. With this in mind, the robot was designed to maximize space and to provide a modular approach without compromising functionality.

2.1.1 Drivetrain and Base

At the base of most every robot is its drivetrain; the way in which it is able to move about the field. Considering that there was simultaneously a time limit and a size restraint on the robot, a robot with a centralized virtual turning center was deemed more desirable, since potentially tight spaces on the field would be difficult to navigate otherwise. This ensures that minimal drift will occur in the robot's position. In order to fit in these tight spaces, and thus not violate the size restriction, an octagonal base of 10.5 inches wide was designed, the shape of which would cascade into the upper sections of the robot. An octagonal base allows the robot to turn without having any corners protrude outward and collide with the walls. A circle could be argued to achieve the same objective whilst saving material cost, but the octagonal base allows the addition of any accessories to be at an equal and consistent angle around the base, hence keeping the robot's weight evenly distributed.

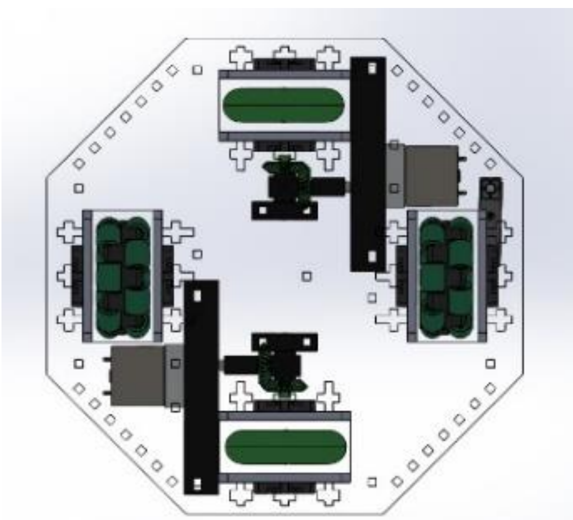


Figure 1: Robot Base

As seen in figure 1, four points of contact were maintained via the two traction and two omni-directional wheels, such that the robot would not tip at any one point during the challenge. The two traction wheels, being situated perpendicular to the pseudo-caster omni-wheels, were each directly powered by a Pololu 37Dx54L mm motor. This was accomplished using 45° beveled gears to divert the physical placement of the motor to the side. Doing so allows the motors available to be used while not interfering with each other. Each of the two traction wheels were directly driven by the aforementioned motors due to the fact that the field does not require any demanding motor output. Additionally, a speaker that played "The Raiders March"- better known as the Indiana Jones theme song- as well "We Didn't

Start the Fire" by Billy Joel, was attached to the base as well to down fire towards the ground and amplify the sound as the soundwaves bounce off the ground.

2.1.2 Mid-section

Residing in between the drive train and the turret (top section), the mid-section, depicted in figure_, housed all the essentials for making the robot operate correctly. Maintaining the octagonal design, the mid-section was designed such that two distinct layers could be used to properly house and implement the necessary sensors and electronics. The first layer, which resided immediately above the drive train, primarily housed the IMU. Along with the IMU were the two motor controllers for the Pololu 37Dx54L motors. Additionally, the 12- and 5-volt batteries used to power the robot loosely resided in this section. Having these components on the bottom layer allowed for conserving space, neatness, and allowing the IMU to be centered on the robot.

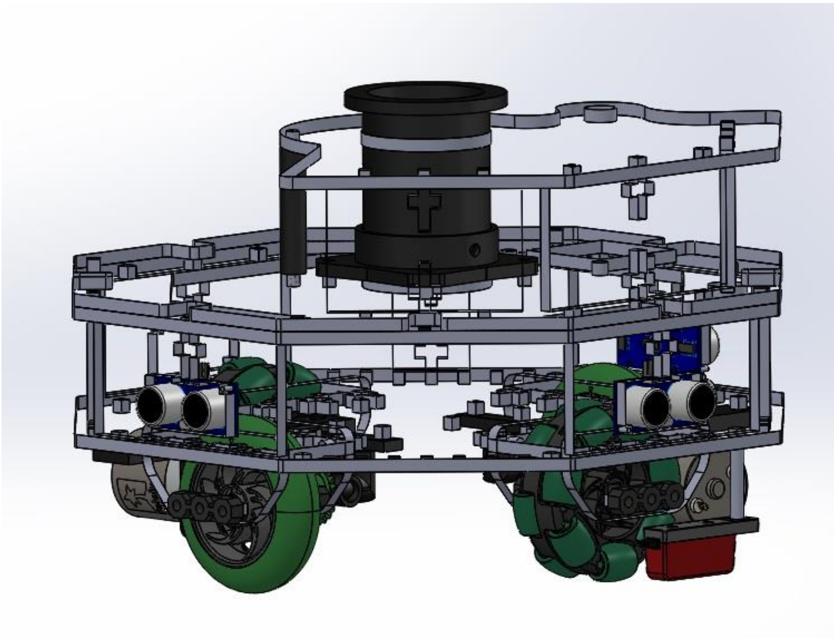


Figure 2: Robot Mid-section

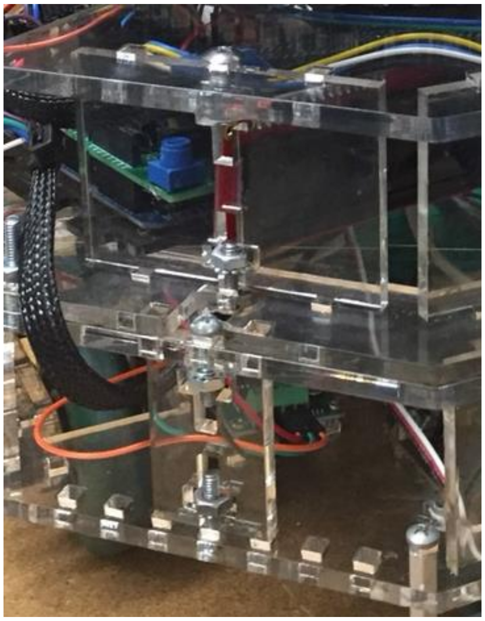


Figure 3: Acrylic Standoffs

Connecting the top layer of the mid-section were acrylic walls, as seen in figure _. These walls served as standoff spacers to add stability and spacing for the wiring. This allowed the top layer to be connected only by a few screws. The spacers were positioned on the sides of the base that did not have any wheels. By placing the spacers in such a position, it allowed for the ultrasonic sensors to be attached to walls of acrylic above and parallel to the front, left, and right wheels separately. Having ultrasonic sensors positioned parallel to the wheels allow for accurate distance-from-wall measurements and straight driving from angle correction based on readings over time.

The top layer of the mid-section holds the majority of the electronics, that will be discussed in more detail later. In addition to the Arduino Mega and Uno, the Bluetooth shield, LCD screen and a communal breadboard all shared this space. It is in this area that the main computation and processing occurred.

2.1.3 Turret

Being the main asset of the robot, the turret, as seen in figure _, was optimized to be free of unnecessary material. Centered on the concept of continuous scanning, a 200 cfm fan, Wii remote, and a Sharp Infrared Rangefinder were all assembled together on a 3D printed block that was mounted to a 100-toothed laser cut gear. This turret base was subsequently powered by a Mercury Nema Stepper Motor. Geared in a 10:1 ratio, the stepper motor's typical 1.8° per step was reduced to 0.18° per step, allowing a greater accuracy in determining the location of the flame with respect to the direction in which the robot was traveling. Care was taken to ensure that any and all wires deemed essential to the operation of the turret components where fed through the 3D printed base of the turret such that, while it was operating, the wires did not get tangled or break at extreme angles.

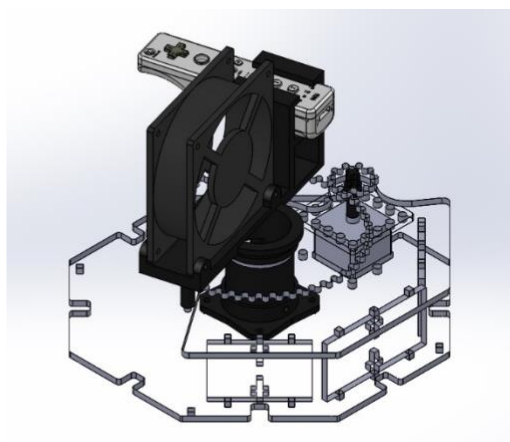


Figure 4: Robot Turret

2.1.4 Modularity

The robot was designed modularly in order to get a base up and running as soon as possible. This way the turret and other sensors were cable of being calibrated and tested for functional operation separately and did not hinder the assembly of the base in order to get the navigation code working. This style of modularity also allowed the robot to be easily disassembled and debugged. The different sections can be disconnected and tested by the means of taking out only a few screws as opposed to taking the entire robot apart.

2.2 | Sensors and Electronics

In order to operate completely autonomously, as per the challenge rules, the designed robot needed to smoothly operate several sensors and electronic subsystems in order to optimize space and processing power. These systems were mounted throughout the robot chassis, as described in the previous section, in order to optimize their separate functionality.

2.2.1 The Fan

The most prominent system, the fan, was selected after careful experimentation. In compliance with the rules stated in appendix A, fire suppression methods such as fire extinguishers or snuffers were immediately disqualified in favor of air based methods. Considering that implementing compressed air would require an additional actuator, several fans were subsequently tested to determine which one would reliably extinguish the flame. After testing several smaller fans, it became clear that a relatively high volume of air would be required to extinguish the flame at any appreciable distance.

From this assumption, two options became clear. The robot could either implement a ducted fan or a larger fan combined with a focusing cone. Fans typically come in either 5- or 12-volt configurations, which presented an issue in terms of the amount of air the fan would blow in cubic feet per minute (CFM). Most 5-volt variants, as well as several 12-volt variants, did not supply sufficient air for their size requirements to be used in the robot. The solution presented itself in the form of the 12-volt fan seen in figure _, which has a 200 CFM rating. In order to power the fan, a 12-volt battery was acquired and promptly wired into a relay on the communal breadboard, which in turn was activated via a digital output pin on the Arduino Mega.

Pololu Flame Sensor vs Wii Remote and Sharp IR
(I need to go into lab and figure out a calibration process such that we can talk about it here, ending with the argument in discussion about why the wii-Sharp IR is better/more reliable)

Pololu Inertial Measurement Unit
UltraSonic sensors
Microprocessors Communication

2.3 | Programming

On an overarching scale, the robot followed the cascading state machine exhibited in figure _ below.

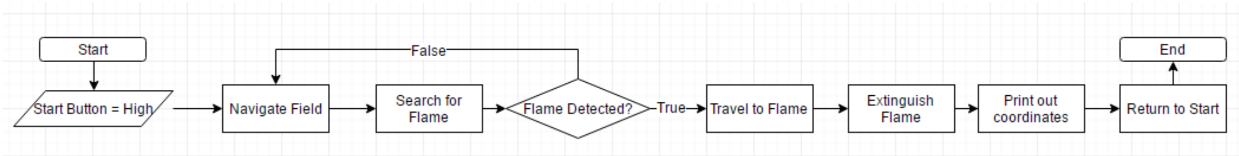
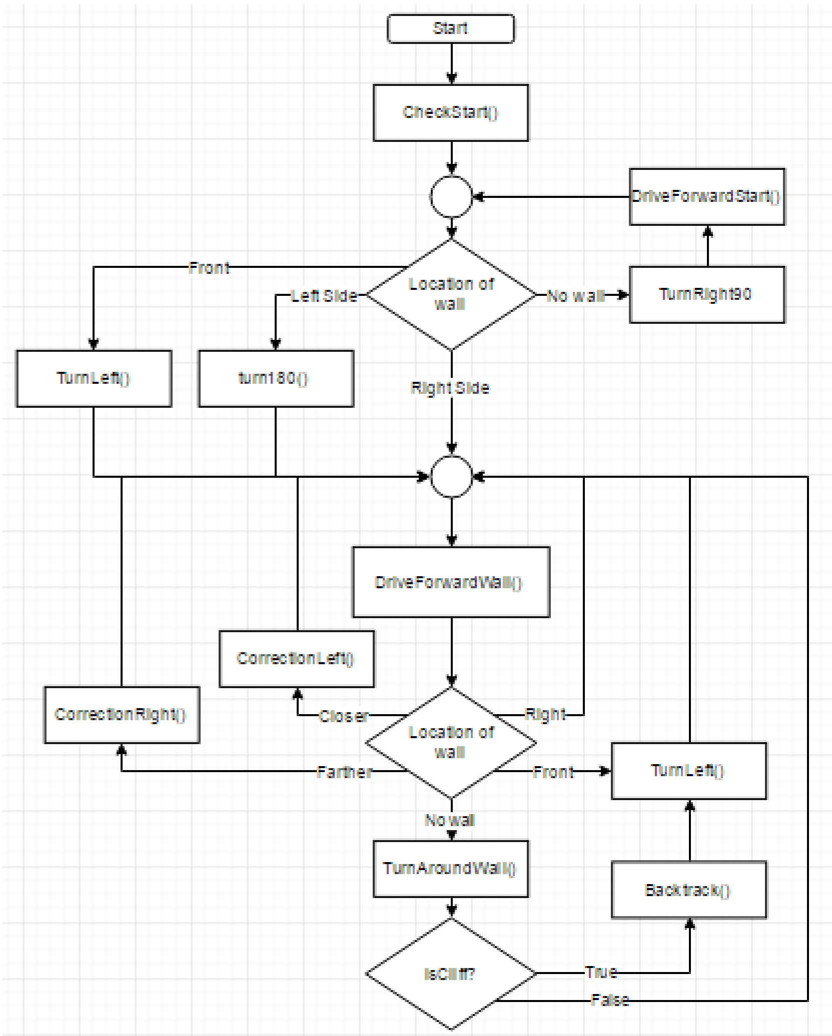


Figure 5: Overhead Programming Flowchart

The robot was designed to run two simultaneous state machines in order to hit the design goal of continuous scanning while moving. The first, and arguably more important, is the navigation state machine, which utilizes input from the various sensors in the mid-section as well as the turret control state machine to determine which state to jump to next. The turret control state machine, on the other hand, receives input from the Wii remote to determine how may steps the stepper motor should take.

2.3.1 Navigation



The complete navigation code can be found in appendix _.

2.3.2 Turret Control

As mentioned prior, the turret control state machine relied upon the Wii remote's ability to detect the candle flame. As seen in figure _, the method employed two main states FLAME_SEEN and NO_FLAME_SEEN, which were for when the Wii remote detected a grouping of infrared and when it did not. Both states relied on were subjected to several

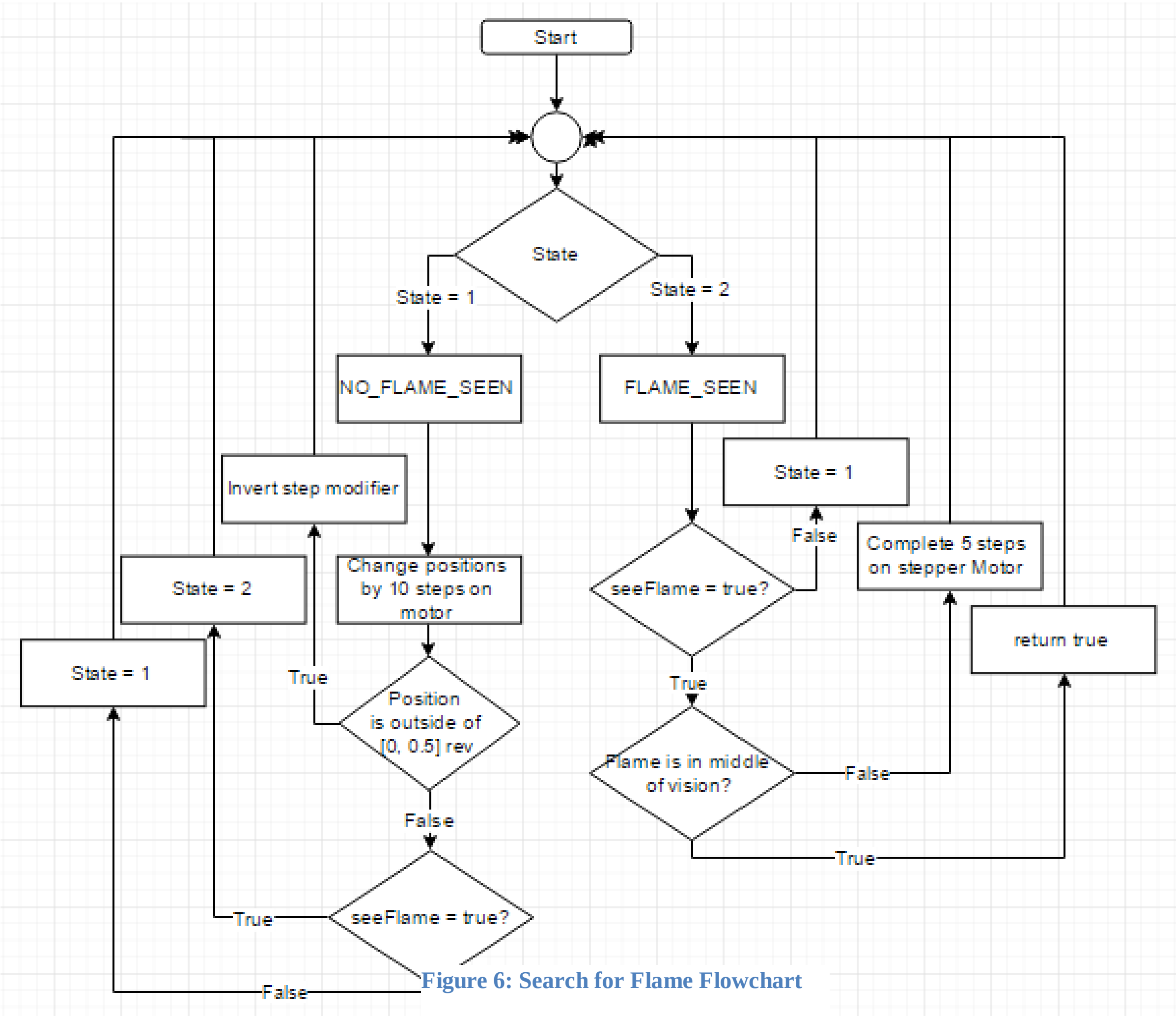


Figure 6: Search for Flame Flowchart

conditional statements to consistently test the status of the flame within the field of view of the Wii remote. If the flame was not seen by the remote, the stepper motor would continue to take ten steps at a time in the same direction until it reached a maximum value. Since the robot followed the right wall due to the navigation code, the turret would only need to scan to the left of the robot. This meant that the maximum values would only need to be 0 and ½ of a turret revolution, in the direction of travel and in the reverse direction respectively.

If, at any point, the Wii remote picked up the candle, the state would immediately switch to FLAME_SEEN. In this state, the Mercury Stepper would take five steps in the direction it was just moving such that the spot of infrared was placed in the center of the Wii remote's field of view, upon which the method would return true to the overhead code, activating a response there. However, if the candle once more passed out of the remote's FOV, the method state would revert back to NO_FLAME_SEEN. The direction in which it turns was decided by a global variable, "mod," which takes the values of -1 and 1, for clockwise and counterclockwise rotation respectively, that is set in the former state, but carries over to the latter once the flame is seen.

The complete turret control code can be found in appendix _.

Section 3: Results and Discussion

3.1 | Sensor Results

Since autonomy is paramount to the operational success of the robot in this challenge, each sensor utilized should be tested to thoroughly understand its individual behavior in response to different situations. As described in section 2.2, the Pololu Flame Sensor was evaluated to determine its effectiveness in discerning the distance a flame was from the robot. The results from this similar experiment can be seen in table _ and figure _.

Distance (inches)	Flame IR Value
3	13
6	16
9	19
12	22
15	24
18	28
21	30
24	35
27	35
30	42
33	52
36	75
39	113
42	141
45	170
48	220

Table _: Flame Sensor Distance Evaluation

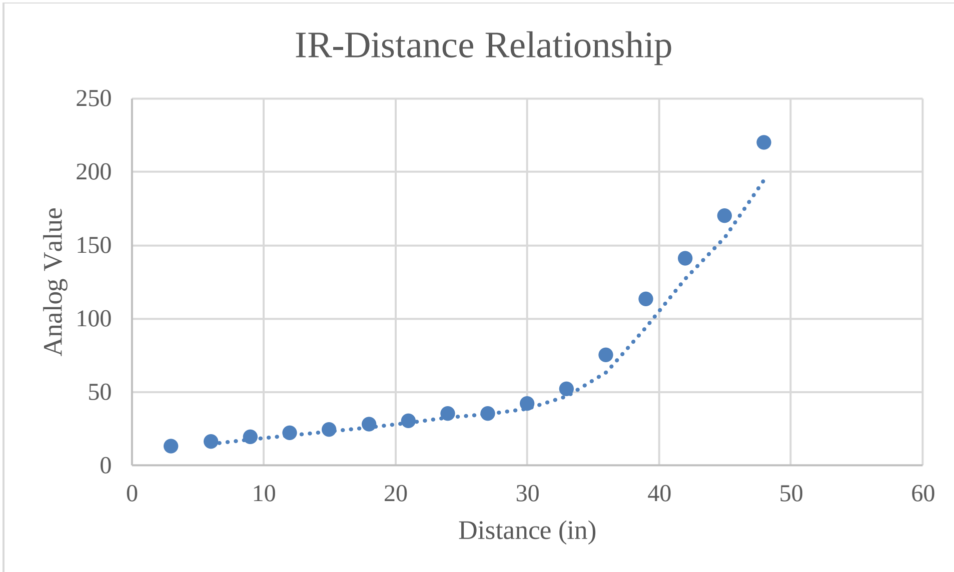


Figure _: Distance vs Analog Value

Additionally, as described in the aforementioned section, the Sharp Infrared Range finder was similarly evaluated for use in determining the linear distance from the flame to the robot. The tabular and graphical results from evaluating the sensor can be seen in table _ and figure _ respectively.

Distance (inches)	Rangefinder Value
6	340
12	171
18	120
24	93
30	75
36	71
42	59
48	58

Table 1: Range Finder Distance Evaluation

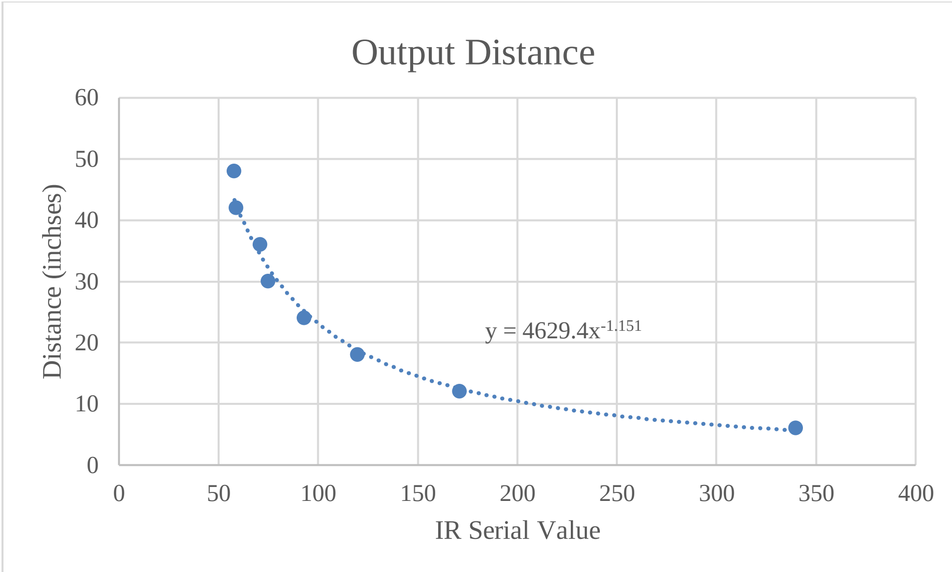


Figure _: Serial Value vs Distance

3.1.1 Discussion

With the Sharp IR Rangefinder and the Pololu flame sensor, it was necessary to determine their respective reliability in determining the distance to the flame. While the two sensors both utilized IR to identify distance, it became clear that the Sharp Range finder was more reliable. As seen in figure _ (FS graph), the Pololu flame sensor exhibited a linear behavior of a particular slope up until approximately 33 inches, after which it assumed a new slope. In addition to the difficulty "seeing" the flame, the flame sensor was deemed too difficult to implement into the main programming, considering no singular equation could be used diagram the behavior of the sensor.

Contrary to this, the Sharp Rangefinder exhibited a consistent behavior over the course the test, as seen in figure_. Relatively exponential in nature, the rangefinder showed some difficulty with evaluating distances within 6 inches, and was very sensitive to distance changes past 42 inches. However, since these values appeared to follow a consistent trend, Excel was used to generate the standard equation below to map the incoming analog values to a distance. This feature was implemented directly into the navigation code as a way to check that the flame was within the operable range of the fan.

3.2 | Presentation Day Results

3.2.1 Discussion

3.3 | Video Resubmission Results

3.3.1 Discussion

3.4 | Future Improvements

Therefore, in the future, steps should be taken in three key areas. First, the essential programming needs to be dispersed from one Arduino Mega to two or more, communicating in I^2C, such that the program(s) can be run at faster rates than if all the processing was done on a singular board, as it was in this case. Second, the programming must be refined to incorporate the redundancy of the ultrasonic sensors, encoders, and inertial measurement unit to ensure straight line travel and accurate coordinates as well as to eliminate any drifting that might occur while driving. Alternatively, a different form of navigation could be implemented that utilizes a form of computer vision to map the immediate area, breaking the reliance on the slower wall following technique. Finally, steps must be taken to reduce the cost and overall cleanliness of the robot in order for it to be considered a household commodity. An iRobot Roomba, which cleans an entire household, is valued at around $400, nearly a hundred dollars less than this prototype.

1	A statement about each result presented, including its significance and how it relates to the project objectives.
2	A discussion of any results that are unexpected
3	A discussion of the causes of experimental uncertainties
4	A comparison of results with theories or preexisting experimental results
5	Personal opinions to explain results
6	If applicable, a description and a comparison of data of any new theory developed on the basis of the test data

Table 1: Discussion Items

Section 4: Conclusion

In an effort to simulate a firefighting version of the iRobot Roomba, the robot was able to autonomously navigate and locate the flame, yet failed at the ultimate goal of extinguishing the flame completely, not for lack of trying. The Wii remote worked admirably in detecting the flame, but the necessary programming was not in place, at that time, to ensure the candle was within the operable range of the fan, as well as allowing the Wii remote to declare. Along with this, the robot did not return to its original starting position. Furthermore, the cost of this one unit was particularly high (see appendix B), with very little reduction in expense with regards to bulk orders of materials.

References

[1]"What chemicals are used in a fire extinguisher? How do they work to put out fires?", *Scientific American*, 2017. [Online]. Available: https://www.scientificamerican.com/article/what-chemicals-are-used-i/. [Accessed: 01- May- 2017].

[2]"Home Fires | Ready.gov", *Ready.gov*, 2016. [Online]. Available: https://www.ready.gov/home-fires. [Accessed: 01- May- 2017].

[3]M. Ahrens, "NFPA report - Home Structure Fires", *Nfpa.org*, 2016. [Online]. Available: http://www.nfpa.org/news-and-research/fire-statistics-and-reports/fire-statistics/fires-by-property-type/residential/home-structure-fires. [Accessed: 01- May- 2017].

[4]"NFPA statistics - Home fires", *Nfpa.org*, 2016. [Online]. Available: http://www.nfpa.org/news-and-research/fire-statistics-and-reports/fire-statistics/fires-by-property-type/residential/home-fires. [Accessed: 01- May- 2017].

[5]C. Putnam, *Lab Assignment 5: Firefighting Challenge*, 1st ed. Worcester, MA: WPI, 2017, pp. 1-2.

Appendix A: Final Project Requirements

INTRODUCTION

In this term-long lab assignment you are required to build a robot capable of navigating a structured environment, finding and extinguishing the simulated fire (a candle), and report the location of the fire in reference to where the robot started. As in RBE 2001, your team will be provided with a Kit of Parts (KOP) which will include an Arduino Mega 2560 and various sensors including a specialized flame sensor.

GOALS

1. Safely navigate the field while avoiding any obstacles that may be found.
2. Find the fire and indicate that the fire has been found.
3. Extinguish the flame and indicate that the fire has been extinguished.
4. Report back the estimated location (X, Y) of the flame using the KOP IMU, encoders, or any other strategy approved by the professor or course staff.
5. The robot must use at least the gyro (part of the IMU), encoders, and a range sensor. Additional points may be awarded for the effective implementation of additional sensors.

PLAYING FIELD

The playing field will consist of a series of walls, cliffs, and obstacles. The approximate size of the field will be 8' x 12'. The candle flame will range from 10 cm to 30 cm above the nominal playing field level. The playing field is <u>not guaranteed</u> to be fully enclosed.

REQUIREMENTS

1. The task must be completed autonomously.
2. The robot should be no larger than a 12.5" cube at the start of the challenge.
3. The robot must indicate when the fire is found and when the fire has been extinguished. [LED's are recommended but not required]
4. The robot must output an X, Y estimate of the location of the fire in inches from the starting location. [LCD screen recommended but not required]
5. In the final report, explain the use and operation of the IR flame sensor. Show a plot of its effective range derived from your calibration data.
6. The robot must complete the task within 5 minutes including the return to the starting position if that is attempted (see optional item 8 below).
7. Optional / Extra Credit: The robot reports the estimated Z location of the fire (in inches from the playing surface).
8. Optional / Extra Credit: The robot returns to its starting position.

RESTRICTIONS

1. The robot must be designed in such a way that it does not combust if the robot comes into contact with the candle.
2. No combustible fluids or gasses may be used. [For example, extinguishing the flame with a flamethrower is unacceptable.]

3. The robot must fit within a 13” x 13” x 13” box at the start of the challenge without touching the walls or top of the box. In other words, the box may not be used to constrain the robot in any way.
4. The robot must remain in contact with the floor of the playing field at all times. Translation: no flying robots!!
5. The robot must operate fully autonomously. The robot may be powered on after it has been positioned on the playing field. It should not begin any driving operations until after a “Go” button has been pressed.
6. The use of water or other liquids is not recommended but is not against the rules. With that said, if you use liquids and there is any damage to electrical components provided to you in the KOP (Arduino, sensors, etc.), your group will be financially responsible for replacing the parts regardless of what happened.
7. Contact with a wall is not allowed. Touching the candle or the candle-holder is not allowed. Contact any of the obstacles on the field is not allowed.
8. If a cliff is present (e.g., if a section of outside wall is missing), the cliff will be marked in such a way that it can be detected by a suitably equipped robot in time to avoid driving over the cliff.

POST LAB
1. Write an excellent lab report including the following sections: Abstract, Table of Contents, Introduction, Methodology, Analysis, Results, Discussion, and Conclusion. Include in your report a cost analysis of your robot, an analysis of the driveline, and an electrical systems analysis.
2. Explain the use and operation of the IR flame sensor and plot its effective range (derived from your calibration data).
3. Describe and discuss any testing done with other sensors used to complete the task. Document how well they worked, problems you had using them, etc.
4. Describe and discuss the mechanism used to extinguish the fire along with any relevant design decisions.
5. Demonstrate good software development and coding practices.
6. Fully document your software procedures, problems encountered and solved, special techniques used, and so forth.

Appendix B: In Depth Cost Assessment

	Item	Quantity	Price	Total
Base	Line Tracker (3 pk)	1	$ 39.99	$ 39.99
	2.75" Omni-Directional Wheel Double Roller (2 pk)	1	$ 19.99	$ 19.99
	2.75" Wheel (4 pk)	1	$ 9.99	$ 9.99
	Metal Gearmotor 37Dx54L mm with 64 CPR Encoder (50:1)	2	$ 34.95	$ 69.90
	Total			$139.87
Mid-section	HC-SR04 Ultrasonic Sensor Distance Module (5pcs) for Arduino UNO MEGA2560 Nano Robot XBee ZigBee by ElecRight	1	$ 9.79	$ 9.79
	MinIMU-9 v3 Gyro, Accelerometer, and Compass	1	$ 11.95	$ 11.95
	MC33926 Motor Driver Carrier	2	$ 17.95	$ 35.90
	Arduino USB Host Shield	1	$ 12.99	$ 12.99
	Arduino Uno Rev 3 with Long Pins	1	$ 24.95	$ 24.95
	Arduino Mega 2560 Rev 3	1	$ 45.95	$ 45.95
	Vex Limit Switch (2 pk)	1	$ 12.99	$ 12.99
	5/16" PET Cable Wire Wrap Expandable Braided Sleeving 8M 26ft	1	$ 7.62	$ 7.62
	helishun hls-14f3l-dc12v-c relay	1	$ 1.00	$ 1.00
	Total			$163.14
Top	Mercury Nema Stepper Motor SM-42BYG011-25	1	$ 17.97	$ 17.97
	Wii Remote Plus	1	$ 39.99	$ 39.99
	Ultra Strong 12cm DC 12V 200 CFM Fan	1	$ 19.99	$ 19.99
	Sharp GP2Y0A21YK0F Analog Distance Sensor 10-80cm	1	$ 9.95	$ 9.95
	Total			$ 87.90
Misc	5 mm Acrylic Sheet	3	$ 21.13	$ 63.39
	0.22" Acylic Sheet	1	$ 19.99	$ 19.99
	Elegoo 120pcs Multicolored Dupont Wire 40pin Male to Female, 40pin Male to Male, 40pin Female to Female Breadboard Jumper Wires Ribbon Cables Kit for arduino	1	$ 8.86	$ 8.86
	Total			$ 92.24
	Grand Total before tax			$483.15
	Grand Total after tax			$513.35
	Personal Contribution Total			$287.42

Appendix D: Authorship

Section	Author
Introduction	Ben Wagner
Methodology	
Results	
Discussion	
Conclusion	