Final Design Review

Sponsor – Richard Emberley

E.M.B.E.R.
HOME PROTECTION

Economical, Mechatronic, Burn-Extinguishing Robot

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Statement of Disclaimer

0. Executive Summary

Despite the increased danger of wildfires in states such as California and Colorado, there is yet to exist a product that can autonomously extinguish the spot fires that ignite from windblown embers. This device could reduce countless civilian casualties and prevent millions of dollars in property damage. This is not to mention allowing homeowners to evacuate with a greater peace of mind. Mass ownership of this product would be analogous to the "herd immunity" of vaccines, where neighbors ultimately protect each other and save money through self-insurance.

There are products on the market, generally in the commercial domain, that can protect a building from wildfire. However, these devices come at a high cost that eliminates even the upper-middle class household. The device we are building is unlike anything in current existence because it utilizes thermal imaging technology to reduce the water consumption related to firefighting.

Through brainstorming and research, an understanding of the scope and specifications involved with this project was developed. These ideas were compiled and compared using various decision-making tools. After working our ideations into one solid design, we performed the necessary analyses and gathered parts and materials. The physical components were manufactured and assembled to create a stationary rotating device with a vertical array of sprinkler nozzles. Upon completion of the mechanical system, it was integrated with an electronic assembly that uses a single-board computer to analyze thermal imaging data from a FLIR camera, control rotation of the device, and dispense water in the appropriate direction.

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1. Introduction

1.1. California Wildfire Severity

The intensification of climate change has only served to exacerbate the severity of California's droughts. With the susceptibility of pockets of dry brush that stretch across the state, the potential for the spread of wildfires is a substantial issue at the forefront of political debate. Fires are no longer seasonal to the state of California, and the Camp Fire (November 2018) remains the deadliest and most destructive wildfire in the history of California, causing 85 civilian casualties and $16.5 billion in damage.

The dangers of a single ember are incredible, as evidenced by the spark from a downed power line that started the Camp Fire. In nature, spot fires hold similar characteristics to the Camp Fire's igniting spark. With the right wind conditions, small embers can launch far beyond the heart of the wildfire, igniting spot fires in neighboring areas. These firebrands destroy millions of acres and hold no preference in their consumption: wildfires can and will destroy both urban development and natural land without much warning.

1.2. Stakeholders and Goals

The cornerstone of any successful design is exhaustive attention to the needs of the consumer. Stakeholder preferences define the product as demand is the backbone of any significant financial endeavor. One of the most substantial facets of this project is that the device must be affordable. Attention to this constraining factor was especially considered during the design and manufacturing phases of our project.

Beyond this, another important consideration is desirability. In a first-to-file country like the United States where patents exceed the millions, it is the unique details of a design that constitute its success in open market. For E.M.B.E.R. (where "mechatronic" and "robot" make up 40% of the entire name: Economical, Mechatronic, Burn-Extinguishing Robot), its autonomous nature is integral to customer attraction. In addition to the significance of wildfire protection, a self-controlled device holds its own inherent intrigue.

1.3. Overview

Chapter 2 of this report lays out the background research conducted, including our customer feedback, existing solutions, and relevant technical literature. In Chapter 3, the results of this research were utilized to determine a problem statement, customer wants and needs, and device specifications. Chapter 4 contains details regarding our initial conceptual prototypes, including preliminary testing and potential risks. Chapter 5 outlines our final design decisions, addressing safety concerns and the final cost. In Chapter 6, we discuss the manufacturing process of the final prototype. Chapter 7 gives a detailed analysis of our specifications and the tests that verified they were met by the device. Chapters 8 and 9 go through our process during the project and make recommendations for the future.

2. Background

2.1. Expert Interviews and Customer Survey

In the first interview with our sponsor, Dr. Richard Emberley gave the team his input regarding the fire aspect of this project. With embers travelling up to five miles ahead of wildfires, he claims that the front of the fire is moving faster than can possibly be imagined. Dr. Emberley explained the two schools of thought on wildfire home defense. The first is leaving your home to do its own thing with whatever defenses already exist e.g. non-combustible roof, separation between urban and wildland. The second is to defend in place i.e. staying behind to spray embers around your home with a hose. This is proven to be an effective method, however, an obviously dangerous endeavor. Dr. Emberley wishes us to find the best of both worlds by creating a device that can put out burning embers after the homeowner has evacuated to safety.

In the second interview with Kelly Fernandez, an operations manager for State Farm Fire and Casualty Company, the team narrowed down our customer base from general homeowners in high-risk wildfire zones. A device of this type is much more likely to sell to those homeowners who are educated on their insurance policy and staying updated with their estimated replacement cost. The more expensive the home, the greater the deductible that will have to be paid should the home be lost to a fire, and the potential discount offered for owning this device would be more significant as well. This leads us to believe that while no one wants to lose their home in a wildfire, wealthy homeowners are going to be more likely to self-insure by buying a product such as E.M.B.E.R.

This idea was proven further by a survey we submitted to the Cal Poly SLO Mustang Parents Facebook page. The survey indicates that more than 75% of people would pay at least $500 for a wildfire home protection device. The results of this survey are posted in Appendix A.

2.2. Existing Solutions

There are several design solutions already on the market that address specific aspects of the fire defense problem. Existing products are further discussed below, and descriptions of related patents are provided in Table 2-1. Through this research, we found that while there are products and systems solving parts of the issue, there are no effective solutions that cover the entire problem as we intend to.

Product 1 | *Firebot*

The Firebot was a senior project with essentially the same goal as ours. They modified and programmed a Whitebox Robotics 914 PC-BOT to detect fire and extinguish it. As exciting as a roaming robot would be, our budget does not support this, and we do not believe that function is necessary to design a successful product.

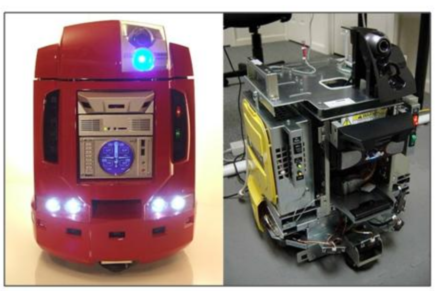

Figure 2-1. Firebot with and without a cover [1].

Figure 2-2. Multiple Firebot devices [1].

Product 2 | *Droplet*

Droplet is a robotic, lawn-watering sprinkler. The smart sprinkler system utilizes cloud computing in order to reduce water consumption up to 90%. This product relies on interconnectivity using

Wi-Fi which is not a goal for our project because power is often cut off during a wildfire evacuation. We prioritized battery life for longevity over communication.

Figure 2-3. Droplet targeting plants to water [2].

Product 3 | *Orbit Yard Enforcer*

The Yard Enforcer is a motion-activated sprinkler that protects gardens from animals and pests. It uses a combination of heat and motion detection to humanely repel wildlife. While Orbit has the same basis as our project, their heat detection is in a far lower range than we intend to work with.

Figure 2-4. Full view of the Yard Enforcer [3].

Figure 2-5. Yard Enforcer in action [3].

Product 4 | *Plumis Automist*

Automist is an indoor fire sprinkler that does not require a tank or commercial incoming water main. It uses less water than a traditional sprinkler system and is triggered by a ceiling mounted heat detector. In comparison, our device will be for outdoor use and function with a more precise fire detection system.

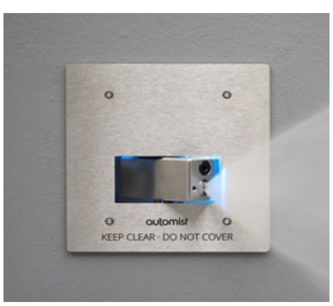

Figure 2-6. Automist Smartscan Hydra [4].

Figure 2-7. Automist Fixed Wall Head [4].

Product 5 | *FOAMSAFE Fire Protection Systems*

FOAMSAFE is an outdoor fire prevention system which, when activated, sprays a biodegradable foam around your property to make it fire resistant. This product helped us realize that it may be beneficial to not merely put out spot fires but to try and prevent them from happening in the first place. This could be done by presoaking the yard, while still trying to conserve as much water as possible.

Figure 2-8. FireMaster System in action [5].

Product 6 | *WASP*

WASP stands for Wildfire Automated Sprinkler Protection and is a gutter-mounted sprinkler system. The product is intended to be left on continuously after the homeowner has evacuated. There a significant amount of water waste associated with this product as it does not involve fire detection.

Figure 2-9. Gutter-mounted WASP system [6].

Figure 2-10. WASP system up close [6].

Table 2-1. Related patents and descriptions.

Patent Name	Description	Patent No.
Automatic Spray Mechanism	The device is a motion-detecting sprinkler to deter animals. The system uses an electronic motion sensor to detect motion and an adjustable spray nozzle which automatically disperses water towards the area of motion.	8,904,968
Robotic Watering Unit	The system receives a map of the yard and determines which areas need water. A mobile utility vehicle provides that water accordingly.	8,322,072
Apparatus and methods for sensing of fire and directed fire suppression	The invention provides proactive and intelligent fire suppression and/or control using a microcontroller that is communicatively connected to at least one fire-energy detection sensor and at least one fire suppression device.	7,066,273
Motion Sensor Alarm and Sprinkler Device	Motion sensors installed around a home communicate with a sprinkler system to detect intruders and intends to scare them away by soaking them with water.	9,633,536
Retractable adjustable-trajectory rooftop fire sprinkler	Comprised of a sprinkler head, trajectory angle setting mechanism, and lockable flow-through hinge fitting. The function is to wet the roof and surrounding area to reduce the threat of ignition from embers.	9,084,907

2.3. Relevant Technical Literature

Table 2-2 displays literature that gives insight to the project scope. The first article explains how fire spreads across a lawn with different environmental conditions. The second article discusses the appropriate amount of water used to fight fires in the most effective and efficient way possible. The article focuses heavily on water conservation which is one of the main design constraints for our project. The third article considers the effect of various sprays and how well they extinguish fire. Flow shape, size, and fire extinguishing capabilities were important to examine in order for our device to extinguish spot fires before they spread. The next article is related to the third and discusses at what angles and heights a sprinkler should be set to achieve desired spray patterns. The last article describes how to build a water control system using microcontrollers which is an integral function of our final design. Table 2-3 provides industry codes that apply to the scope of the project.

Table 2-2. Relevant technical literature.

Article Title	Description	References
Modeling Wind Adjustment Factor and Midflame Wind Speed for Rothermel's Surface Fire Spread Model	This article details the fire spread model adjusting for various environmental conditions.	https://www.fs.fed.us/rm/pubs/rmrs_gtr266.pdf
Water vs. Fire	A guide to effectively fighting forest fires.	https://wildfiretoday.com/documents/WaterVsFire.pdf
Fire suppression by water sprays	This article details the use of water as a suppressing agent, identifying the benefits and gaps of knowledge that exist.	https://www.sciencedirect.com/science/article/pii/S036012859900012X
Influence of the trajectory angle and nozzle height from the ground on water distribution radial curve of a sprinkler	This article evaluates the effects of variation of height and angle of a sprinkler nozzle on water distribution.	https://www.agroengineering.org/index.php/jae/article/view/jae.2012.e4/3
Design and Construction of Microcontroller-Based Water Flow Control System	This article describes how to design and build a water control system using microcontrollers.	https://pdfs.semanticscholar.org/8fcb/e383dbe54defeffffc9fc93aeb25e3fa674a.pdf

Table 2-3. Applicable industry codes.

Code	Description	References
Model Water Efficient Landscape Ordinance (§490)	This code describes how landscapes should help in fire prevention, and only the water reasonably required for beneficial use shall be used.	Barclays Cal. Code of Regulations - Department of Water Resources
Water Waste Prevention (§493.2)	This code outlines the requirements for preventing water waste.	Barclays Cal. Code of Regulations - Department of Water Resources

3. Objectives

3.1. Problem Statement

Homeowners need a way to automatically suppress small scale fires that occur around their houses to prevent the fire from spreading to their homes and surrounding homes. Many homeowners in high risk wildfire areas currently have no way to defend against flareups other than manually staying behind and using a hose themselves. The product solution must be reasonably priced and easy to set up.

Figure 3-1 shows the boundary diagram designed by our team. This is a visual depiction of both the uncontrollable and controllable factors of the project. Inside the red box are the things that the team has control over while designing E.M.B.E.R. This includes the side of the house, electrical outlets, and water spigot. Further from the house is the lawn, our main concern, where the spot fires that the product will be extinguishing are present. Outside of the red box are the uncontrollable factors, such as the wildfire creating the embers and the main portion of the house. If the house were to ignite, the product would no longer be effective.

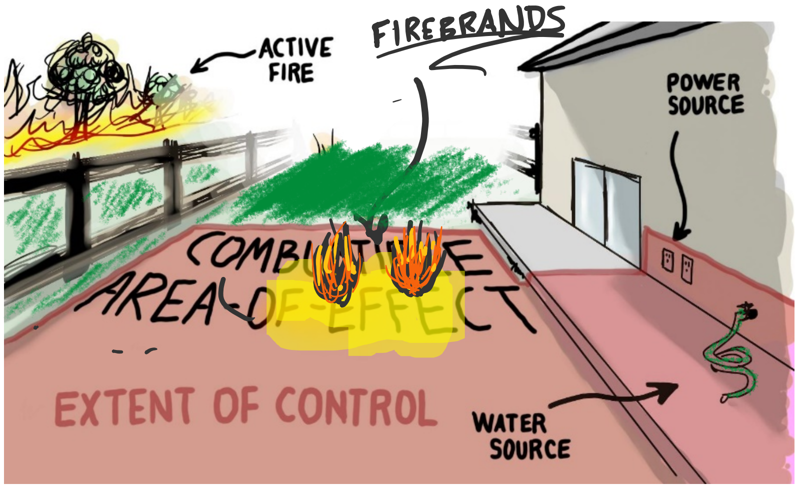

Figure 3-1. Boundary diagram.

3.2. Customer Wants and Needs

Table 3-1 lists the wants and needs of the customer. This list was developed using personal knowledge and experience, the customer survey, expert interviews, and our additional research. Refer to Appendix A for a copy of the survey results. The needs are critical requirements that the project must meet to be defined as successful. The wants are additional, non-critical design goals.

Table 3-1. Customer wants and needs.

Needs	Wants
Fully automated	Inexpensive
Extinguish spot fires	Small
Work without home power	Easy to set up
Cover entire yard area	Aesthetically pleasing
Connect to a hose	User interface
Be robust and sturdy	

Quality function deployment is a tool used to ensure that a product fulfills the customers' wants and needs and meets necessary engineering specifications. QFD makes the design process more efficient by ensuring that no time is wasted designing and building to unnecessary specifications.

Our team developed a QFD using Table 3-1 and the specifications listed in Table 3-2. The engineering specifications are measurable deliverables for the project. Next, a strength of correlation was determined between the wants and needs and specifications to decide if there were any redundant or missing specifications. Finally, some alternatives to our project were compared in order to figure out if it was worthwhile to continue designing E.M.B.E.R. or if an existing design is superior. When the House of Quality in Appendix B was finished, it became clear that there are no better alternatives to E.M.B.E.R., and we had a comprehensive list of specifications to design around.

3.3. Engineering Specifications

Table 3-2. Engineering specifications.

Specification		Requirement or Target	Tolerance	Risk**	Compliance*
1	Weight	Under 20 pounds	Max	M	T
2	Water Resistance	Up to IPX 5	Min	M	T
3	Manufacturing Cost	Less than $250	Max	H	A
4	Coverage Area	At least 2,000 square feet	Min	H	T, A
5	Water Accuracy	Target within one foot	Max	H	T, A
6	Set Up Time	Under 15 minutes	Max	L	T, S
7	User Complexity	Involve no technical setup from the user	Min	L	I
8	Weather Resistance	Maintain functionality in windy conditions	Min	M	T, I
9	Fire Detection	5-inch diameter fire at 25 feet	Max	H	T, A, I

**L = Low, M = Medium, H = High

*T = Test, A = Analysis, I = Inspection, S = Compare to existing products

Specification Measurement

1. Weight will be measured with a standard scale.
2. Water resistance will be measured by visual inspection in order to ensure the device is functional after being exposed to sustained, low-pressure water jet spray (IPX 5).
3. Manufacturing cost will be measured by compiling a Bill of Materials for the cost of all parts.
4. Coverage area will be tested by measuring the maximum spray distance in an open area using a standard garden hose.
5. Accuracy will be measured by the distance from a controlled fire location to the center of the area being sprayed with water while the fire is being targeted by the camera.
6. Set up time will be measured by testing a group of people to see how long it takes them to get the device up and running.
7. User complexity will be measured by checking whether the final product needs any technical input from the user.

8. Weather resistance of the device will be measured by testing the spray distance during high winds.
9. Fire detection of the camera will be tested with a constant fire size at varying distances.

High Risk Specifications

Specification #3 – Keeping the manufacturing cost under $250 may be difficult to achieve based on the complexity of this project. Acquiring the thermal imaging camera and batteries adequate for an extended runtime may lead to a relatively high manufacturing cost.

Specification #4 – Meeting the 2,000 square feet of coverage area specification could prove difficult given the propensity of high wind during a wildfire, making it difficult to project water very far.

Specification #5 – The water accuracy specification is one of the most important for this device to meet as the device must be accurate in order to function effectively. High accuracy may be difficult due to the potentially broad range of system variables. However, with a relatively wide spray of water, spot fires can be extinguished regardless of slight inaccuracy.

4. Concept Design Development

4.1. Ideation and Decision Matrices

Our initial process to develop a large quantity of rough ideas was participating in three separate ideations sessions. An example of these initial ideas can be found in Table 4-1. We broke down the brainstorming into various functions pertaining to our project scope including: 1) mounting and rotation, 2) nozzles and fluids, 3) camera and electronics, 4) packaging, and 5) miscellaneous. Appendix C contains an example of the ideation results. Progressing on the concepts developed during these sessions, we further developed each function by comparing and contrasting solutions available to the categories individually. These options were put into Pugh Matrices that allowed us to narrow the scope of the project into four major functions and evaluate their best solutions. The four sections were fire detection, water dispersion, motion, and electronics. A copy of our Pugh Matrices is found in Appendix D. The top-ranking alternatives were the FLIR Lepton camera, oscillating sprinkler, DC motor, and Raspberry Pi, respectively. We created various combinations of the functions and compared these complete concepts with a Weighted Decision Matrix. This can be found in Appendix D, as well, and assisted greatly in the selection of our chosen design.

Table 4-1. Top conceptual ideas.

Concept Model Photo	Description
	The first concept design was a two-camera system with integrated adjustable spray. By changing the nozzle area, water velocity can be increased or decreased to hit various targets. This concept focused only on the top portion of the overall design. The increased cost of using multiple cameras eliminated this option.
	The second idea incorporated an oscillating sprinkler equivalent to the one we use in our final prototype. This design only involved one camera because with the vertical array of nozzles and horizontal oscillation of the sprinkler, our system did not need to account for depth perception, negating the need for a second camera.
	The third concept design was cylindrical, using only a single spray nozzle which can adjust its angle vertically and rotate horizontally to target a fire. The tube exiting the bottom is the hose connection for the homeowner. All tubing within the device is fixed. We did not move forward with this concept because it requires additional motors, as well as two cameras.
	The fourth idea was a "shotgun" approach, wherein there are a large number of nozzles exiting the top of the device. This allowed for a fire in any direction to be suppressed, and the yard can quickly and easily presoak to prevent future fires. There is a massive amount of water waste associated with this concept leading us to move forward with more complex systems.
	The fifth concept design had four nozzles whose rotational motion was powered by fluid momentum rather than mechanical power. The cylindrical shape allowed for easy rotation of the device. While lowering power consumption, this idea did not solve the issue of increased water expenditure.

4.2. Selected Concept

Through research and evaluation of the decision matrices, our team came to a conclusion that blends the best solution for each project function. For fire detection, we decided that the FLIR Lepton thermal camera is superior due to its detection distance and accuracy. The only negative is the Lepton's high cost. However, relative to thermal cameras on the market that meet our needs, the price is reasonable at $70 wholesale. For water dispersion, we chose an oscillating sprinkler because it is by far the best option as it scored high among all criteria. An oscillating sprinkler is cost effective and accurately dispenses a vertical sheet of water as far as 25 feet. For rotational motion, a DC motor, much like the oscillating sprinkler, proved to be a clear unanimous winner in all fields. These included cost, speed, accuracy, and power efficiency. Lastly, for electronics, we used a Raspberry Pi computer, the highest rank in the Pugh Matrix. This decision was based on cost effectiveness and memory capacity relative to its easy interface.

Once these choices were made, we began the process of constructing a concept prototype. The selected model consisted of two parts: 1) a stationary base and 2) a rotating top housing. The base included a hose connector protruding from the side for the homeowner to attach their garden hose to, as well as a turntable device that rotates the top housing. The turntable is driven by a DC motor, which is mounted to the top housing. Located in the rotating top housing is the oscillating sprinkler and thermal camera positioned vertically above the sprinkler to get the highest vantage point possible. Figure 4-1 shows a photo of the concept prototype. A preliminary CAD drawing of this concept is found in Figure 4-2.

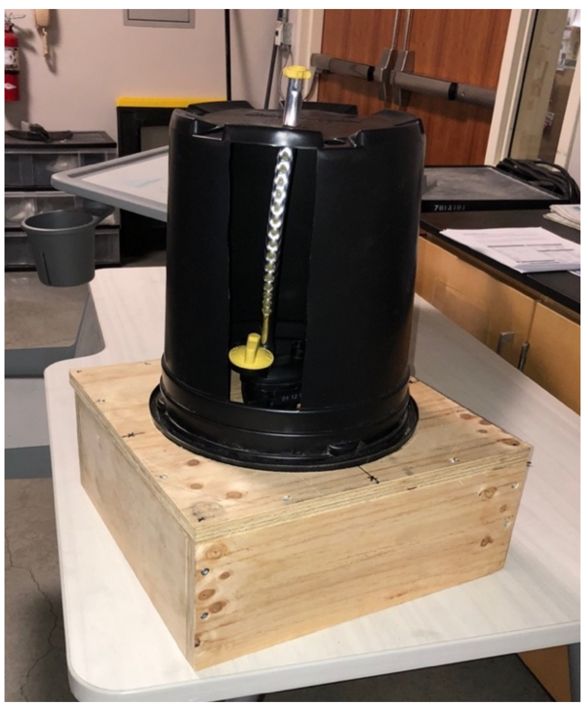

Figure 4-1. Concept prototype.

The base dimensions were not yet solidified; however, the rotating top housing is 8 inches in diameter and approximately 14 inches tall. For the final prototype, the base and housing were constructed out of PVC pipe. As for the concept prototype, we chose to build a square wooden base and use a plastic bucket for the top as this was simple to manufacture. The main component of our concept that was still under review was the connection between the base and rotating top housing. We researched and developed the best way to integrate a motor and turntable assembly into our design, as described in Chapter 5.

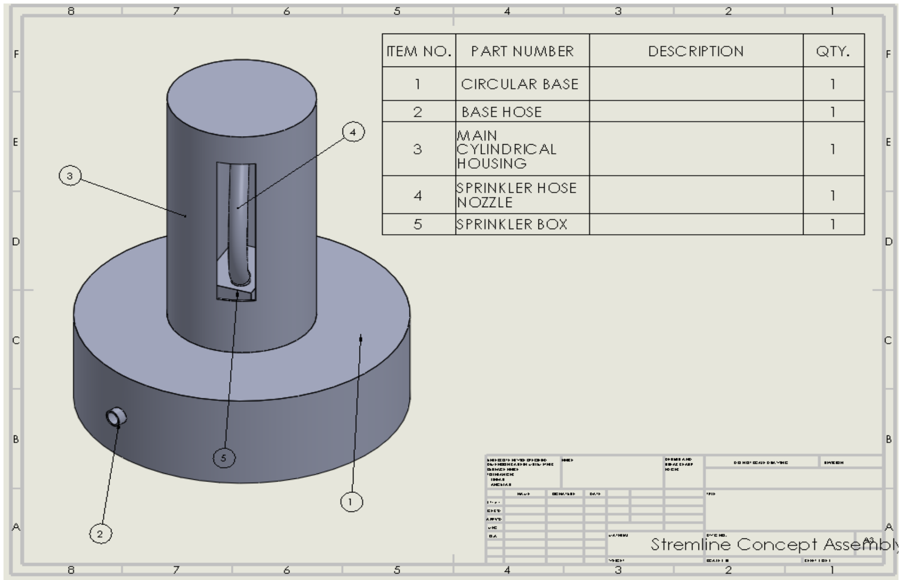

Figure 4-2. Initial concept CAD with BOM.

4.3. Preliminary Analysis and Tests

Our team performed a handful of preliminary tests, mainly focused on the water distribution of the oscillating sprinkler we used. One of the primary specifications this device must meet is the ability to effectively dispense water in a circular area of about 2000 square feet (a radius of 25 feet). We ran the first test at maximum hose water pressure, which was 60 psig in this case, and measured the maximum spray distance of the oscillating sprinkler when positioned vertically. From this test, we concluded that the maximum distance was 30 feet, but the volume of water dropped sharply after 25 feet. Up until this cutoff distance, the water distribution appeared very even and accurate.

The second test we ran involved measuring flowrate to quantify the water consumption of our sprinkler. We attached a flowmeter to the hose and measured the flowrate, Q (gpm), at various water pressures, P (psig), to get a range of Q values based on spray distance. Figure 4-3 contains a plot detailing the flowrate data we gathered compared to Newtonian projectile motion. Even at maximum pressure, the flowmeter showed a relatively small flowrate of 4 gpm. In addition, after running the sprinkler for a 5-minute interval, approximately 4 ounces of water collected in a 3-inch diameter cup. Extrapolated out, this corresponds to 16 ounces of water per square foot in a minute. We obtained this data by setting up cups at 5-foot increments and measuring the volume of water that gathered in a set amount of time.

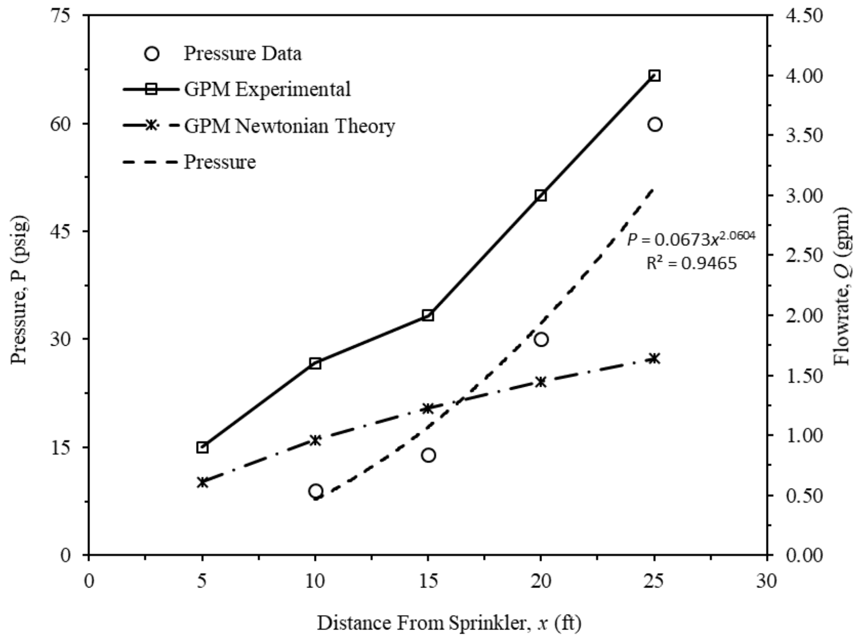

Figure 4-3. Pressure and flowrate vs. spray distance for experimental data and Newtonian theory.

4.4. Risks, Challenges, and Unknowns

The anticipated challenges with our chosen final design were creating the camera housing, preventing hose kinking and wire entanglement during rotation, and keeping power consumption low to maximize battery life. After meeting with engineers at FLIR, it was recommended that we use a germanium lens as part of the camera housing for the Lepton. However, the potential issues with this germanium lens included cost (roughly $200), fragility, and inexperience with the material. A potential solution the FLIR engineers mentioned was using Saran Wrap instead. Though not as elegant of a design, this was the most probable solution. Through testing, we discovered both Saran Wrap and Ziploc bags are sufficient lens materials.

As the top housing rotates relative to the base, our flexible hose and wires were likely to kink and tangle. The way we combated this issue was installing a continuous coupling to prevent hose kinking and limiting the rotation of the device to 190^0 in either direction rather than an uninterrupted 360^0. We believe this does not limit the device functionality in any way.

Our last potential challenge was keeping power consumption low. Since our battery is running a DC motor, Raspberry Pi, solenoid valve, and thermal camera, we needed to focus on power expenditure. We chose electronic components with low power consumption that are still adequate for our project needs.

Risks and safety hazards were analyzed regarding our prototype design. The Design Hazard Checklist allowed us to run through potentially dangerous scenarios and determine if there were ways to minimize the risks associated with E.M.B.E.R. Descriptions of the related hazards along with plans to correct for them are located in Appendix J.

5. Final Design

5.1. Description and Functionality

Final decisions for the device were made and a structural prototype was built, shown in Figure 5-1 below. This prototype tested the final concept and geometry using cheaper materials. A picture of the final device prototype is found in Figure 5-2.

Figure 5-1. Structural prototype.

Figure 5-2. Final confirmation prototype.

Starting at the base of our design, there are three 9-inch long metal stakes fixed to the bottom that allow for stabilization in the yard of a user. Housed in the stationary base is flexible hosing that routes water into the device from a garden hose, through an electric solenoid valve, and into the oscillating sprinkler through the center of the rotational assembly. That assembly consists of an 8-inch gear fixed to the top of the base and lazy Susan that is fixed to the gear on its bottom frame and motor mounting plate on its top frame. The motor mounting plate, discussed further in Chapter 6, aligns the motor and pinion to allow for a mesh between the gear and pinion.

When the motor is running, the pinion acts as a planetary gear rotating around the sun gear and causing the top housing to rotate. The top housing contains the FLIR Lepton thermal camera, oscillating sprinkler, and Raspberry Pi. The rotation of this housing is necessary because the camera needs to scan its surroundings in search of a spot fire and aim the device in that direction before releasing water. Both the base and top housing are cylindrical with diameters of 8 inches. The hose that runs through the device allows for continuous rotation through a swiveling coupling on the sprinkler, but the wires that run from the computer to the solenoid valve in the base must not become tangled. Therefore, rotation is limited to one revolution before the device changes direction. An encoder on the DC motor allows for this limitation to be controlled. Due to a complication with the SPI communication of the Lepton camera, encoder, and Raspberry Pi, the team was unable to implement our encoder software with the camera software. Therefore, at the Senior Project Expo, an indicator light was used to demonstrate that water was being supplied rather than connecting the solenoid wires. While the SPI interface of the encoder functioned as expected, the chip select logic of the camera was reversed meaning that the Raspberry Pi was unable to distinguish between which device it was received data from. A solution to this problem could be using a processor that has internal quadrature decoding capabilities or changing the feedback to a limit switch that indicates when a revolution has been reached. Figure 5-3 below contains a CAD rendering of the final design.

Figure 5-3. Confirmation prototype CAD rendering.

A wiring diagram depicting the electrical layout of our device is shown in Figure 5-4. A state transition diagram that lays out the software function of the device is shown in Figure 5-5. Refer to Appendix F for a copy of all software code.

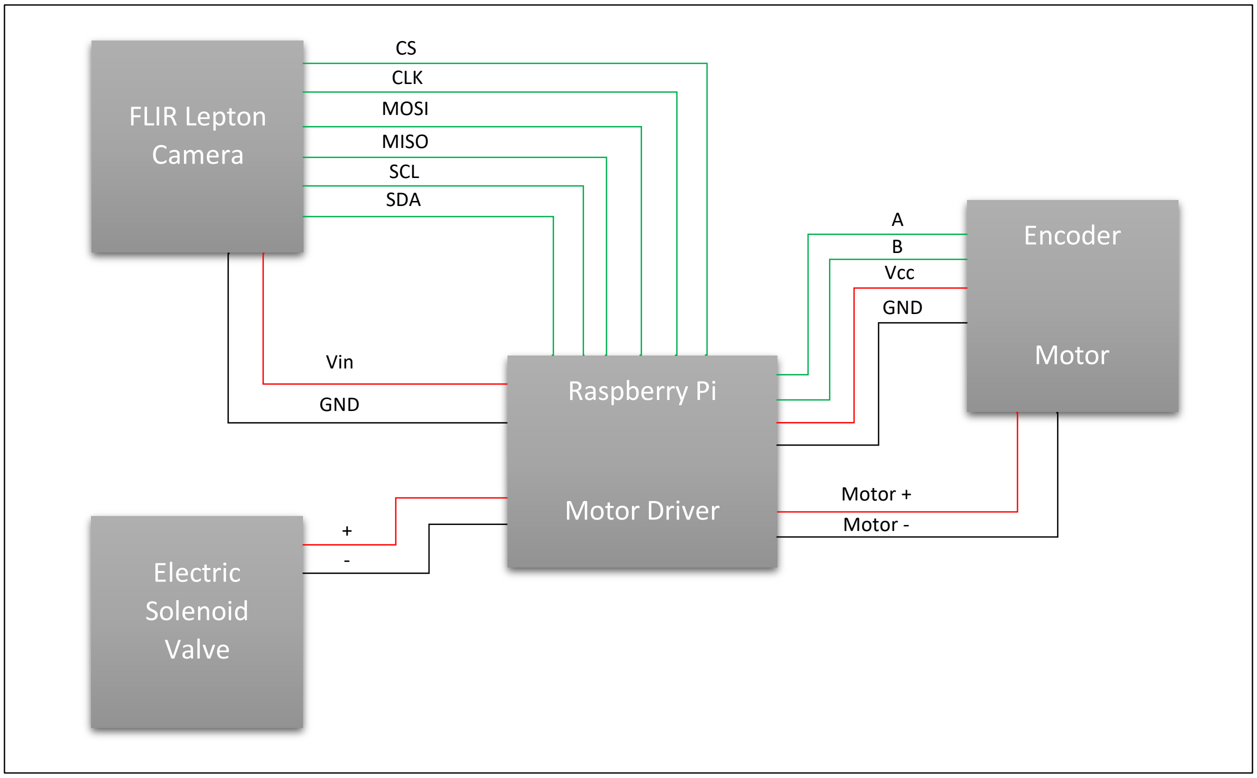

Figure 5-4. Electrical wiring diagram.

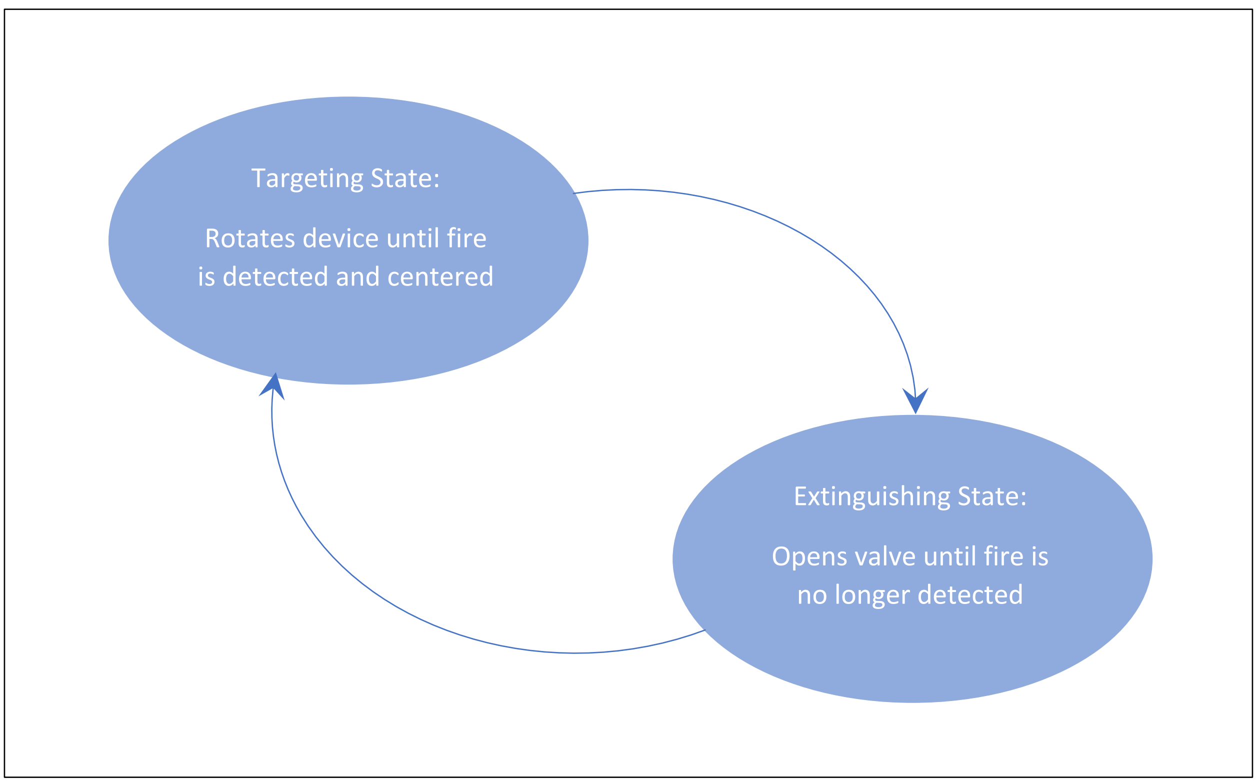

Figure 5-5. State transition diagram for E.M.B.E.R. software.

5.2. Evidence

We conducted analysis that indicates our final design will meet or exceed the specifications in Table 3-2. Starting with weight, we procured 8-inch diameter PVC pipe that weighs 5.6 pounds per foot. The device is roughly 25 inches tall making the weight of both housings 11.67 pounds. The solenoid valve weighs 1.6 pounds. The rest of the device includes the sprinkler (roughly 1 pound) and the lazy Susan, 3-D printed gears, adaptors, and flexible hosing (2 pounds total). The camera and camera housing are of negligible weight. Therefore, the final weight of our device is approximately 16.3 pounds which satisfies the desired specification of 20 pounds.

To meet the water resistance specification of our device being IPX 5, we designed the electronics to be housed in a Pelican case which satisfies an IPX 5 rating and added thread seal tape to the fluid connections. The sprinkler nozzle window is sealed with flexible plastic.

The desired coverage area of 2000 square feet represents a spray radius of approximately 25 feet which is within the range of our chosen sprinkler. We conducted water distribution analysis, as described in Section 4-3, showing that the device can shoot up to 30 feet with low wind. We also conducted accuracy testing and analysis showing that the device can dispense 16 ounces of water per square foot in one minute. This test proved that E.M.B.E.R. can sufficiently soak a targeted area demonstrating that the accuracy specification of targeting within one foot is achievable.

Since the device is meant to be a consumer product, we designed it to be very easy to set up. The software requires no user input; all the user has to do is install the device into the ground with stakes, connect their water hose to the hose adaptor, and turn on the power switch. From there, the software begins scanning, targeting, and spraying as necessary. This design satisfies both the set-up time and user complexity specifications.

The last specification which proved difficult to meet was the weather resistance specification, specifically in windy conditions. We performed tests in mildly windy conditions, and the results were less than ideal. The maximum spray distance decreased from 30 feet to roughly 15 feet during wind speeds of approximately 10 mph. High wind significantly affects the range of spray; however, it does not disable the functionality of our device. We performed extensive calculations showing that the stakes provide sufficient stabilization in wind up to 56.5 mph. Detailed analyses are found in Appendix H.

5.3. Safety, Maintenance, and Repair

Considerations for the safety of E.M.B.E.R. were made during the creation of a Failure Modes and Effects Analysis. This analysis is tabulated in Appendix I. While a majority of the potential failure modes and effects had high severity ratings, their occurrence ratings were almost all very low. The condition of the top housing failing to rotate is the only failure mode with an occurrence greater than 5. The two failure modes with the highest priority were the loss of integrity of the base and top housing outer material due to cracking or breaking. However, the PVC pipe we chose for these components is highly resistant to impact force. An additional Risk Assessment was made, found in Appendix K. This supported the creation of an Operators' Manual, located in Appendix L. Instructions and advice are given to assist the user in properly setting up and operating the device.

The ability to maintain our product and repair broken pieces is dependent on access to its internal components. There are acrylic sheet panels that seal the top and bottom of the device. Both will be removable with brackets. Once removed, there is access to not only the internal components but the nuts and bolts holding the rotational assembly together. This aids in repair of the electronics, gears, or lazy Susan should that be necessary.

5.4. Cost Analysis

The cost to build the final prototype was greater than the initial amount given by our specification. However, this is mainly due to the fact that the FLIR Lepton camera and breakout board were donated to our project by FLIR. If these two parts are removed from the equation, the cost is reduced to $220.48 which meets our goal. When we initially created our manufacturing cost specification, it was with the assumption that we would use a far cheaper thermal camera since the team did not have a relationship with FLIR at the time. Table 5-1 below contains the current prices of the device components. If this product were to be mass manufactured, the cost would be far less as the components would be optimized and procured at wholesale prices rather than list prices. A more detailed indented Bill of Materials is located in the Drawing Package in Appendix E. A portion of these purchased materials were used to build the structural prototype in Figure 5-1.

Table 5-1. Simplified Bill of Materials with cost.

Part Descriptions	Cost
8-inch PVC Pipe and Metal Stakes	$58.98
Oscillating Sprinkler and Electric Solenoid Valve	$40.60
Raspberry Pi and Water Resistant Case	$65.00
FLIR Lepton Camera and Breakout Board	$109.99
DC Motor with Encoder and Acrylic Mounting Plate	$39.00
3D Printed Gears and Lazy Susan	$4.48
Flexible Hose and Hose Adaptors	$12.43
Total Cost	$330.48

6. Manufacturing

6.1. Procurement

The necessary materials and purchased components were acquired. Table 6-1 details each part and where they were bought from. Continuing the cost analysis from Chapter 5, we achieved our goal of keeping the project budget as low as possible while maintaining a proof of concept. We received the most expensive components, the Lepton camera and breakout board, from FLIR as a donation. In addition, our team received MESFAC funding for a large portion of the other parts. Our project advisor provided the remaining components including a Raspberry Pi and motor driver breakout board.

Table 6-1. Procured parts and materials.

	Component	Procurement Location	Procured (Y/N)
Base	8" Diameter PVC Pipe	Farm Supply Store	Y
	Electric Solenoid Valve	Amazon	Y
	5/8" ID Flexible Hose	Home Depot	Y
	Plastic Hose Adaptors (x4)	Home Depot	Y
	Metal Stakes	Home Depot	Y
Rotational Assembly	Lazy Susan	Home Depot	Y
	Sun and Pinion Gear	Cal Poly & Daniel Santoro	Y
	DC Motor with Encoder	Robot Shop	Y
Electronics	FLIR Lepton 3.5 Camera	FLIR	Y
	Raspberry Pi 3	Cal Poly & Project Advisor	Y
	Breakout Board for Lepton Camera	FLIR	Y
	Plastic Lens for FLIR Lepton	Grocery Store	Y
Top Housing	8" Diameter PVC Pipe	Farm Supply Store	Y
	Oscillating Sprinkler	Amazon	Y
	Water Resistant Pelican Case	Amazon	Y

6.2. Manufacturing Process

Manufacturing started with the rotational assembly. The 3D printed sun gear was attached to the top of the base with steel-reinforced epoxy. The bottom of the lazy Susan was attached to the top of the sun gear with four threaded bolts. Four more threaded bolts attached the top of the lazy Susan to the motor mounting plate. The top housing is attached to the mounting plate with four 90-degree brackets. Due to interference between the lazy Susan and motor mounting plate bolts and the top housing, a portion of the top housing PVC pipe was drilled out to allow the pipe to sit flush. A photo of the rotational assembly is shown in Figure 6-1. A piece of stiff, cylindrical plastic was wrapped around the outside of the rotational assembly to guard against pinched fingers.

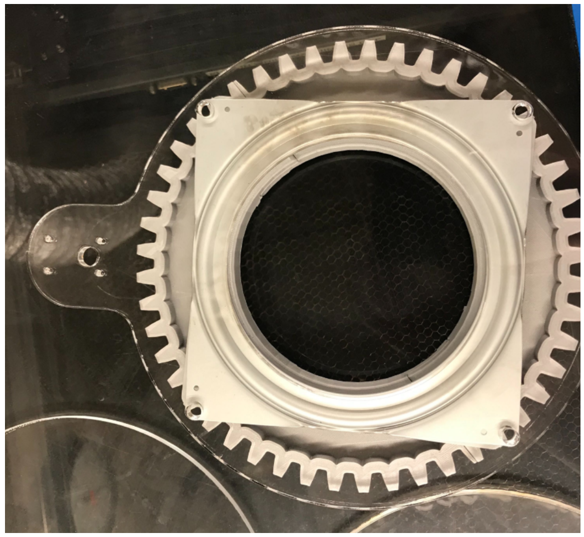

Figure 6-1. Motor mounting plate, lazy Susan, and gear assembly.

The sun gear was 3D printed out of PLA and the pinon gear was printed out of PETG. The pinion gear has 12 teeth and a pitch diameter of 2 inches, and the sun gear has 48 teeth and a pitch diameter of 8 inches. Their drawings are shown in Figure 6-2. The motor mounting plate was custom manufactured from a laser cut ¼-inch acrylic sheet, and the lazy Susan was a purchased part. A CAD drawing of the custom mounting plate is shown in Figure 6-3.

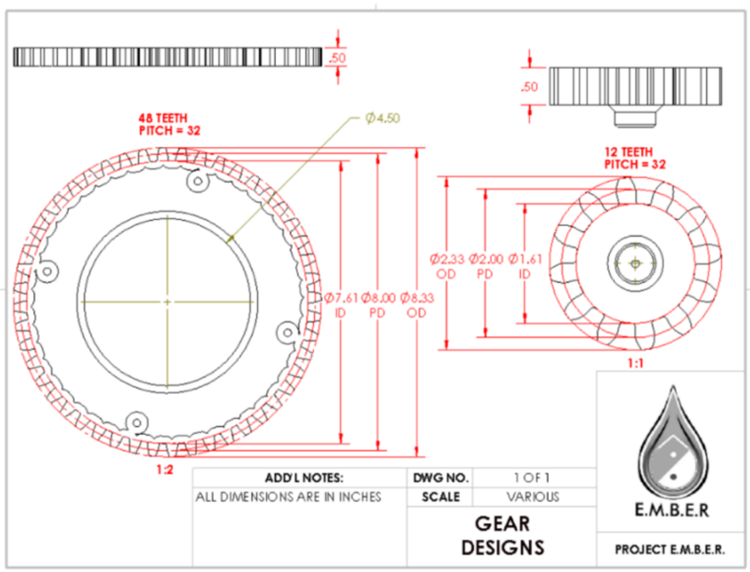

Figure 6-2. Sun and pinion gear engineering drawing.

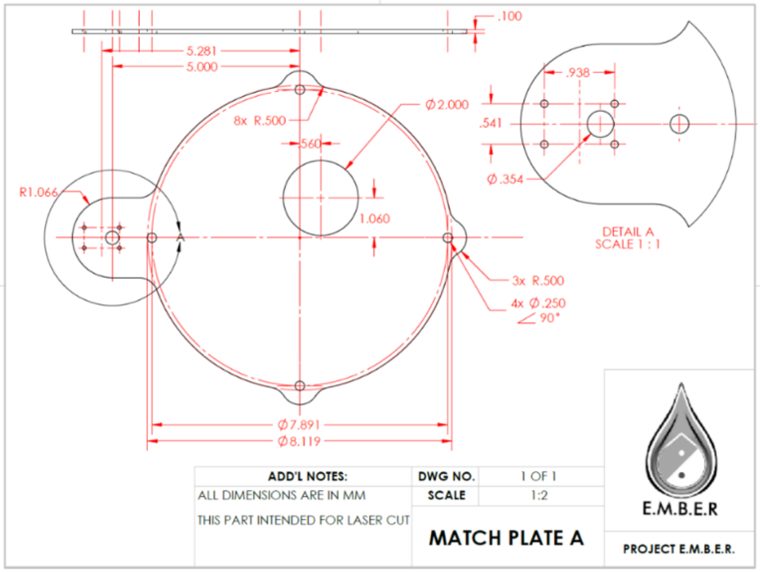

Figure 6-3. Motor mounting plate engineering drawing.

Because the gears and motor mounting plate were the only major custom components, the manufacturing process mainly involved assembly of purchased parts. The electric solenoid valve was mounted in the base using a two-hole strap attached to a custom wooden spacer that allowed the 90-degree tube adaptor to be centered in the device. In addition to the two-hole strap, the garden hose connector attached to the inlet of the solenoid valve provides added mounting support.

The sprinkler was attached using custom wooden spacers that create a slot within a two-hole strap at the top and bottom of the nozzles. Their shape is pictured below in Figure 6-4. The custom spacers have a concave section that the sprinkler tube fits inside, and this prevents the tube from rotating with clamping force from the two-hole straps.

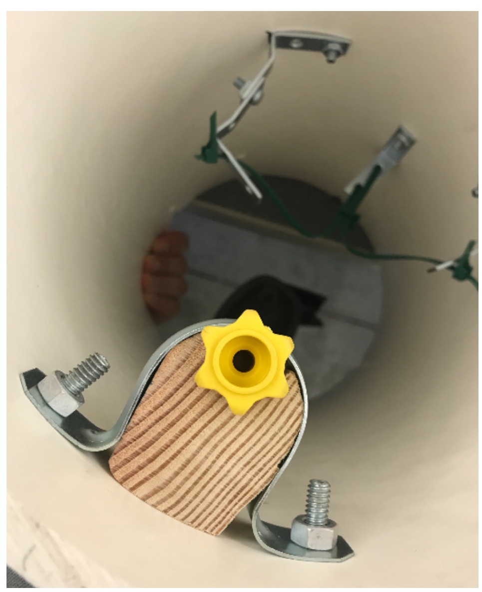

Figure 6-4. Sprinkler mount.

The last major manufactured component was the Pelican case mount. The Pelican case holds all of the electronic components to protect them from water. The case was mounted using 90-degree brackets attached to the inner wall of the top housing. To create a net that holds the bottom of the Pelican case while it is inserted in the mount, we attached a series of zip ties that have a basket effect. This design allows for the case to be easily inserted and removed. A photo is included below in Figure 6-5.

Figure 6-5. Pelican case holder.

We designed this device to be relatively modular. All components can be disassembled with the exception of the epoxied gear and base connection. The fluid piping and valve wires run through the center of the device to avoid tangling as the device rotates. There are multiple threaded fluid connectors that can be used to separate the base and top housing if necessary.

6.3. Challenges and Recommendations

A manufacturing challenge that we encountered in the Cal Poly Machine Shop involved the press fit of our DC motor into the 3D printed pinon gear. Due to relatively unpredictable expansion in the printed gear, it was difficult to precisely size interference with the motor shaft. While attempting to press the motor into the pinion gear, there were two issues. One, the 3D printed gear cracked from the stress, and two, the motor shaft jammed requiring us to redesign the motor and gear connection. We decided to continue working with a 3D printed gear, however, we recommend laser cut acrylic as a future solution. Rather than press fitting the motor shaft into the gear itself, we purchased an aluminum wheel hub that matches our shaft diameter and drilled this into the pinion gear. This allowed the motor shaft to be held to the gear using a set screw.

7. Design Verification

Table 3-2 lists the design specifications that were laid out for the project. This chapter describes each specification in more detail and explains the test plans and testing results. Full test procedures are found in Appendix N. Appendix M contains the tabulated DVP&R. Refer to Table 7-1 for the design verification test results.

7.1. Test Plans

Weight

The initial maximum weight chosen at the beginning of the project was 5 pounds, but after further design and research it became clear that this was an unrealistic goal to achieve the necessary rigidity to leave the device in a yard year-round. The maximum weight was increased to 20 pounds, mainly due to the weight of the 8-inch diameter PVC pipe being used for the top and bottom housing. The rigid PVC makes the device robust enough to withstand the impact of small objects and the force of the water leaving the sprinkler.

To verify the maximum weight of the device, we used a standard scale to measure the weight of the completed device in pounds.

Water Resistance

The device should be water resistant to a rating of IPX 5. This means that the device is able to withstand being sprayed by a water jet from any direction. The level of water resistance rating was chosen due to the high pressure in the water hose. The device should continue operating even if the water hose begins to leak. This rating also covers rainfall which is important because the device may be outside year-round.

The Raspberry Pi and motor driver are housed in a Pelican case in order to achieve the necessary electrical water resistance. To test the water resistance level, the case is closed and then sprayed with a hose at close range for a minute. Then the inside of the case is inspected for water.

Manufacturing Cost

The manufacturing cost requirement is $250 or less. This was difficult because the Lepton thermal camera and breakout board cost about 40% of this alone. We understand that the cost to build a prototype is greater than the cost to mass manufacture, and therefore, hoped to keep the prototype cost within range of this specification. This was verified using our indented Bill of Materials found in Appendix E.

Coverage Area

The required effective coverage area is 2000 square feet. This means that the device needs to have an effective radius of approximately 25 feet. The biggest obstacle to achieving this goal was the wind. The streams leaving the sprinkler are thin and break up into small droplets of water therefore making them susceptible to wind effects. The test to verify weather resistance is described below.

The nominal coverage area was verified by running water through the device with the valve open and measuring the maximum spray distance in standard wind conditions.

Accuracy

The device must be accurate so as not to waste water and be effective in extinguishing spot fires. To make the device as accurate as possible, the camera is facing the same direction as the array of sprinkler nozzles. This way, when a hot spot is located in the center of the camera pixel array, the sprinkler is also in line with the observed hot spot.

To test accuracy, the device repeatedly attempted to extinguish a small fire. The fire was set up 15 feet away from the device, and when the camera detected fire in the center of the pixel array, it sprayed water for 15 seconds. Each time this was repeated, we measured the distance from the center of the spray to the fire. This deviation was used to calculate the standard deviation of the accuracy of the device.

Set Up Time

To make the device as user-friendly as possible, it was decided that the device should take no more than 15 minutes to assemble and set up for use. This was tested by simulating how the device would be packaged in a box and tasking people with various skill sets to open the box and set up the device as instructed. Each participant was timed, and the times were recorded and analyzed to obtain the average set up time.

User Complexity

In achieving the goal of user-friendliness, not only does the device setup need to be quick, but it should be achievable by any level of technological experience. This means that the device should be operational when the user turns on the power switch and not involve any electronic set up aside from charging the battery. This was verified by following the procedure for the previous specification.

Weather Resistance

The device must be resistant to inclement weather. The effects of wind and rain were discussed earlier in this section. Weather resistance was explicitly placed on the specifications list to reiterate the negative effect weather can have on device performance. The water resistance test verifies the ability to withstand rain. To verify device operation during high wind, we will perform the following test.

The effective distance sprayed by the device will be measured on a windy day. Wind speed will be measured by an anemometer. If the conditions are not windy enough, a fan will be implemented to increase the effect. By comparing maximum distance and wind speed, we can develop a performance curve for the device.

Fire Detection

This final specification is the most important to the success of the project. Spot fires must be detected by the camera in order for the device to perform as expected. The camera is most accurate at determining the temperature of a location if the average area covers 10 pixels. The team determined that a spot fire 5 inches in diameter covers about 5 pixels at 25 feet from the camera. This distance corresponds to the maximum spray distance.

To verify that the Lepton camera can distinguish the change in temperature over such a small area to determine if a spot fire is present, we performed the following test. The test involved taking pictures of a 5-inch diameter fire at distances of 5 to 30 feet and analyzing the camera array to count the number of pixels that see a temperature greater than 350 degrees Kelvin.

7.2. Test Results

Table 7-1 displays the testing results determined by the multiple tests described in the previous section. For the tests that were completed, each of the design specifications were verified with the exception of manufacturing cost and water resistance. The lack of success with the cost specification was anticipated and discussed in Section 5.4. We strongly believe that a company mass producing a product similar to our project will have no problem reducing the cost to well under the goal of $250. Refer to Appendix G for a complete Project Budget. The water resistance test was not run on the Pelican case after it was modified to allow wires to pass through. The holes in the case would need to be sealed before its final water resistance can be evaluated.

Table 7-1. Design verification test results.

Specification	Requirement or Target	Test Result	Verified?
Weight	Under 20 pounds	17.9 pounds	YES
Water Resistance	Up to IPX 5	TBD	NO
Manufacturing Cost	Less than $250	$330.48	NO
Coverage Area	Radius of 25 feet	Radius = 25 feet	YES
Water Accuracy	Target within one foot	Target within 4 inches	YES
Set Up Time	Under 15 minutes	Less than 5 minutes	YES
User Complexity	User only attaches hose and switches on power	User only attaches hose and switches on power	YES
Weather Resistance	Maintain functionality in windy conditions	Fire extinguished during wind	YES
Fire Detection	5-inch diameter fire at 25 feet	5-inch diameter fire at 30 feet	YES

During the water accuracy test, thermal images from the Lepton camera were taken while the device extinguished a small fire in a metal fire pit. In Figure 7-1, the sprinkler stream can be seen in the top of the left-hand image. The right-hand image shows that there are no more pixels detecting a temperature over 350 Kelvin. This verifies that the fire was extinguished at 15 feet with less than 10 seconds of water dispersion.

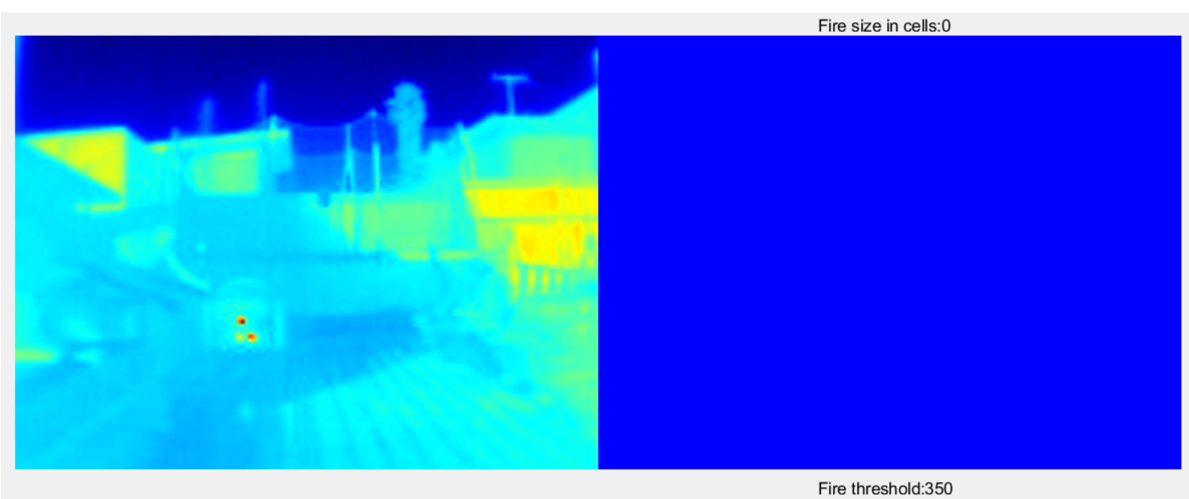

Figure 7-1. MATLAB thermal image and corresponding color mapped CSV image.

Although the full weather resistance test involving an anemometer was not performed due to lack of equipment, a modified version was executed. During a period of wind approximately 14 mph, the device was tasked with extinguishing a fire 15 feet from the device. The fire was extinguished within 10 seconds proving that the device is ultimately functional in windy conditions. This is mainly due to the spray having a 2 to 4-foot width depending on distance from the device.

Figure 7-2 is a conditionally formatted Excel spreadsheet containing temperature values in Kelvin for each pixel of the Lepton camera. This image was taken during the fire detection test at a distance of 25 feet from a small 5-inch fire. At a fire detecting limit of 350 Kelvin, there are 5 pixels detecting fire to use for aiming the device. This met our design specification for E.M.B.E.R. fire detection capabilities.

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Figure 7-2. Camera array with pixel values of a 5-inch diameter fire at 25 feet.

8. Project Management

Through the end of Spring 2019, a rough structure of the prototype was built including the rotational assembly of the gears, acrylic motor mounting plate, and lazy Susan. At the start of Fall 2019, the last quarter of this senior project, the team continued manufacturing and assembly of the final confirmation prototype. This included mounting the sprinkler nozzles, solenoid valve, Pelican case, and Lepton thermal camera. Throughout much of the assembly process, custom mounts and brackets were created to accommodate space and size limitations e.g. the sprinkler and Pelican case mounts. In tangent with the final assembly of the prototype, software development was continued, working toward thermal camera and motor integration.

The physical assembly of the prototype progressed smoothly with no major issues arising. However, the software development posed a major problem related to the encoder. This issue is discussed in further detail in Chapter 5. Interestingly, one of the most successful components of the device, the FLIR Lepton camera, gave us some of the biggest challenges. The camera is small and accurate with high resolution, allowing for precise and consistent fire detection. Nevertheless, interfacing with the camera proved to be relatively difficult and complicated.

Ultimately, the confirmation prototype functioned correctly and nearly all engineering specifications were met. Though the encoder could not be implemented, the goal of demonstrating a proof of concept was achieved. The Gantt Chart in Appendix O provides a detailed layout of the 30-week process.

In regard to team collaboration, implementing a Slack workspace was essential for communication and coordinating project activities. OneDrive allowed the team to work simultaneously on important documents and deliverables. Progress was tracked using Team Gantt to set deadlines and goals for the various aspects of the project to be completed. Teamwork throughout the three-quarter project was cohesive, and we were able to leverage individual strengths to complete tasks on time and eventually design and build a successful prototype.

9. Conclusions & Recommendations

9.1. Discussion and Reflection

The scope of this project was to create an automated sprinkler device that detects and suppresses small spot fires. Specifications for this device can be found in Section 3.3. Based on responses to a Facebook survey and interview with an operations manager for State Farm Fire and Casualty Company, we determined the target customer and ideal price that consumers are willing to pay. The target customer was determined to be upper-middle class homeowners living in medium to high risk wildfire areas. The ideal price point was $500 because 75% of survey respondents indicated that they would be willing to pay at least this much for a device such as ours.

We narrowed the project down to a single design that combines the best solution for each function listed in the Pugh and Weighted Decision Matrices. We believe this resulted in an efficient, effective, and affordable design. An initial CAD model and concept prototype were developed, found in Section 4.2. Data obtained through a preliminary sprinkler test determined that the selected sprinkler has adequate range, accuracy, and efficiency to meet the required specifications.

Following refinement of the prototype design, we proceeded to analyze individual components. It was important to ensure the preemptive success of these parts. After ordering the necessary parts and materials, construction began first on a structural prototype and then on the final confirmation prototype. At this point in time, the main focus became working on the software to interface with and analyze data from the FLIR Lepton thermal camera. Further testing was necessary to characterize how small fires would be seen by the camera, which meant it was crucial to get this aspect of the project functioning as quickly as possible.

The physical structure consisted of a cylindrical housing that was stationary at the base and rotated at the top. A DC motor was used to accomplish this with a planetary gear system. As this manufacturing was completed, we could test the motorized function of the device. Due to the mechatronic nature of this project, it was difficult to begin verification of the electrical components before the mechanical assembly was finished.

Programming for this project was done on a Raspberry Pi using the Python language. This high-level programming language was chosen for its familiarity among the team members. Creating software for the Lepton camera was our biggest setback. It took approximately 10 weeks to properly operate the camera and retrieve the 160 by 120-pixel arrays of temperature data that were essential to the success of this project. These temperature arrays are used to aim the device and ensure fire is extinguished.

During design verification testing, a program was written that stored data from the camera and created videos depicting normalized images side by side with images of pixels above the fire temperature limit. These videos along with successful test results verify that the device autonomously detects spot fires and extinguishes them with water in a 2000 square foot area.

9.2. Next Steps

The most critical next step to further the project would be implementing a method of ensuring that the solenoid valve wires do not tangle and snag as the device rotates. Due to the issues described in Section 5.1 regarding camera and encoder communication, a workaround must be designed. Potential solutions could proceed in two directions: finding a different way to limit rotation or eliminating the need to limit rotation entirely. By implementing a slip ring around the fluid hose, the valve wires, and therefore the device, could rotate continuously. This would make the device fully functional with the software previously designed. The biggest downside to this solution is cost. Slip rings with through holes cost approximately $40, which is expensive relative to the other mechanical components. On the other hand, alternatives to limiting rotation could be finding a processor that communicates with the encoder internally or using a limit switch. STM32 microcontrollers are capable of interfacing directly with a quadrature encoder. Using a limit switch would be an affordable solution because they cost around $1. Writing the code for the limit switch should be straight forward and use a callback function that is triggered by the switch and causes the device to change its direction of rotation.

Additional next steps include improving fabrication of the device, such as the gear material and geometry. Also, improving the complexity of the fire detection software to keep track of the location of spot fires extinguishing previously. By including a second Lepton camera, which would add depth perception but increase the cost, a more sophisticated nozzle design could be used to target fire in two axes.

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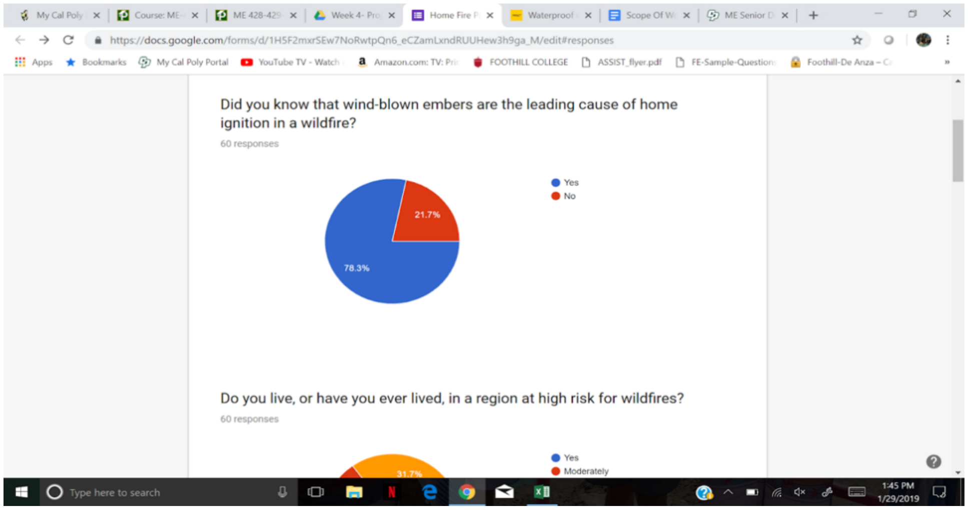
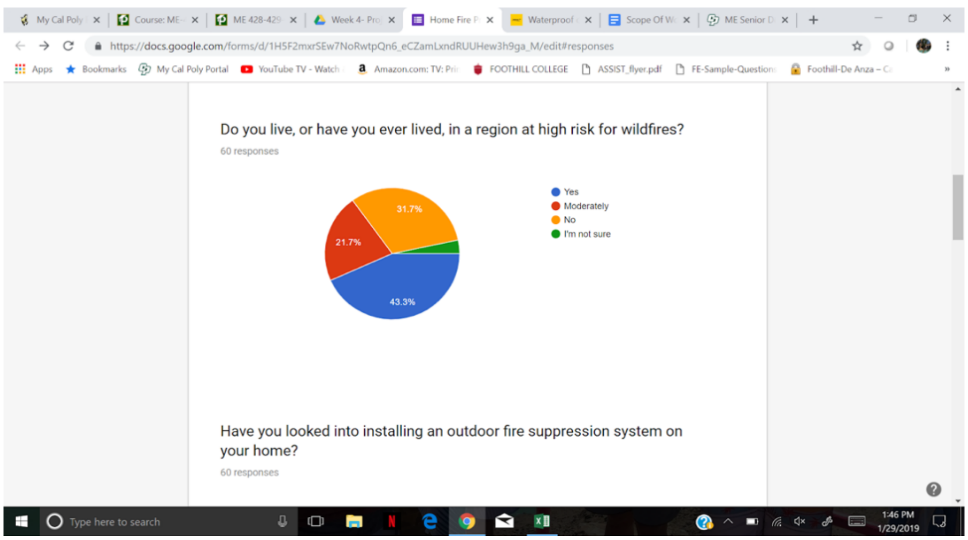
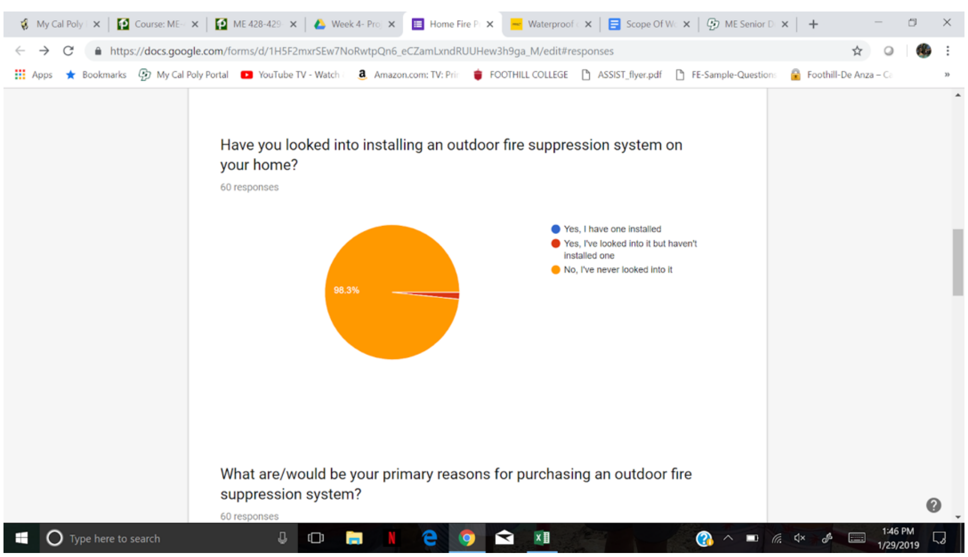
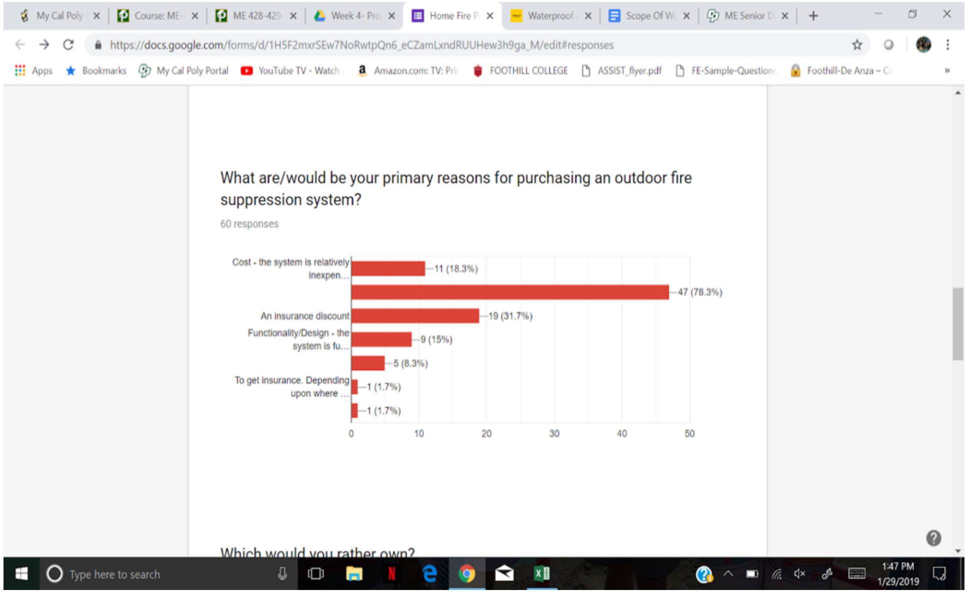
Table of Appendices

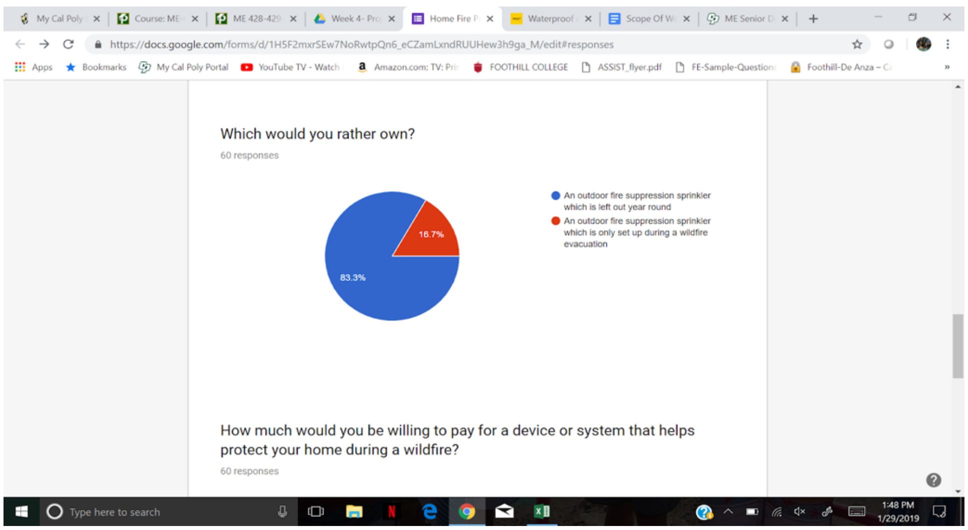
A. Customer Survey

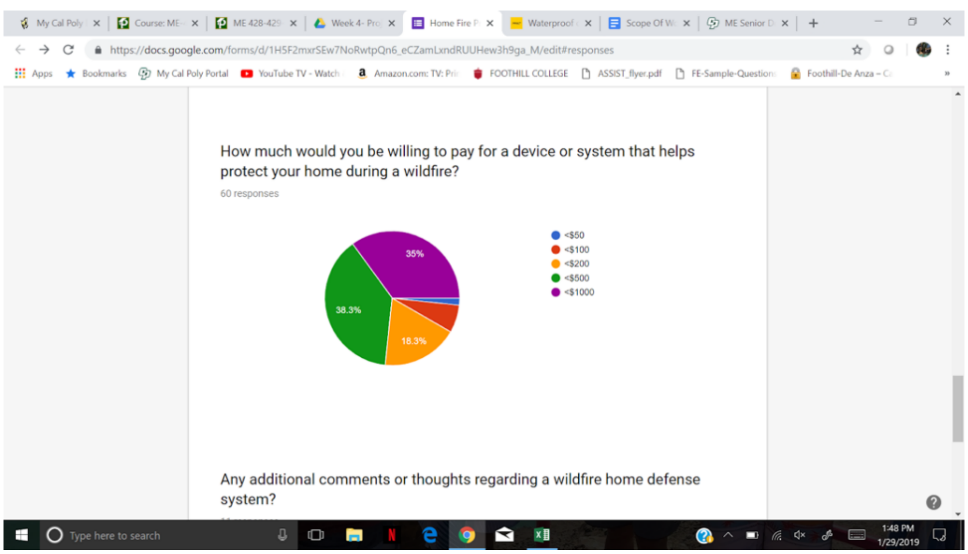







What are/would be your primary reasons for purchasing an outdoor fire suppression system?
60 responses
Cost - the system is relatively inexpen...
An insurance discount
Functionality/Design - the system is fu...
To get insurance. Depending upon where ...
11 (18.3%)
47 (78.3%)
19 (31.7%)
9 (15%)
5 (8.3%)
1 (1.7%)
1 (1.7%)
0
10
20
30
40
50
Which would you rather own?


Which would you rather own?
60 responses
An outdoor fire suppression sprinkler which is left out year round
An outdoor fire suppression sprinkler which is only set up during a wildfire evacuation
16.7%
83.3%
How much would you be willing to pay for a device or system that helps protect your home during a wildfire?
60 responses


How much would you be willing to pay for a device or system that helps protect your home during a wildfire?
60 responses
<$50
<$100
<$200
<$500
<$1000
35%
38.3%
18.3%
Any additional comments or thoughts regarding a wildfire home defense system?

B. QFD House of Quality

Correlations	
Positive	+
Negative	–
No Correlation	

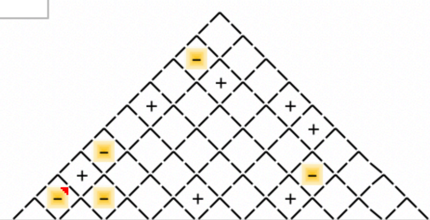
Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

QFD House of Quality

Project: E.M.B.E.R.

Revision Date: 11-16-19



			WHO: Customers						Column #	1	2	3	4	5	6	7	8	9	NOW: Curr. Products					
									Direction of Improvement	▼	▲	▼	▲	▲	▼	◇	◇	◇						
Row #	Weight Chart	Relative Weight	Wealthy Homeowners	Average Homeowners	Commercial Domain	Government	Maximum Relationship	WHAT: Customer Requirements (Needs/Wants)	HOW: Engineering Specifications (Tests)	Weight	Water Resistance	Manufacturing Cost	Coverage Area	Water Accuracy	Set Up Time	User Complexity	Weather Resistance	Fire Detection	E.M.B.E.R.	Firefighter	Hoser on a roof	Leave sprinkler on	WASP	Row #
1		5%	3	8	2	1	9	Affordability		▽	▽	●	▽	▽	▽	▽	○	▽	4	5	5	3	2	1
2		4%	5	5	1	1	9	Small Size		●	○	○	○	▽	○	▽	▽	▽	3	0	2	4	5	2
3		6%	7	7	1	1	9	Easy/Quick Installation		○	○	▽	▽	▽	●	●	▽	▽	5	4	5	5	4	3
4		14%	10	9	8	8	9	Full Automation		▽	▽	○	○	●	○	○	▽	●	5	5	5	5	3	4
5		12%	8	8	7	6	9	Safety		▽	●	▽	▽	○	●	○	○	●	5	4	0	4	4	5
6		12%	7	7	7	7	9	Continuous Operation		▽	▽	○	○	○	○	○	●	○	4	3	3	5	5	6
7		8%	5	2	5	7	9	App Connectivity		▽	▽	▽	▽	▽	▽	●	▽	▽	2	1	2	1	2	7
8		6%	7	5	2	2	9	Desirability		●	○	●	●	○	○	●	▽	○	4	4	1	2	4	8
9		10%	4	5	6	7	9	Sturdiness		●	●	○	▽	▽	▽	▽	●	▽	5	4	2	3	4	9
10		7%	3	8	3	3	3	Power Efficiency		▽	▽	○	▽	▽	▽	▽	▽	○	4	5	3	4	4	10
11		10%	6	8	6	5	9	Large Coverage Area		○	▽	▽	●	○	▽	▽	▽	●	4	5	2	5	5	11
12		6%	6	7	1	2	9	Low Water Consumption		▽	▽	▽	○	●	▽	▽	▽	●	4	1	2	0	1	12

HOW MUCH: Target Values	1	2	3	4	5	6	7	8	9
	Under 20 pounds	Up to IPX 5	Less than $250	At least 2000 sqft	Target within 1 foot	Under 15 minutes	No technical setup	Functional in wind	5-inch diameter fire at 25 feet
Max Relationship	9	9	9	9	9	9	9	9	9
Technical Importance Rating	291.6	304	282.9	303	342.2	314.1	337.9	304.5	488.2
Relative Weight	10%	10%	10%	10%	12%	11%	11%	10%	16%

Curr. Products	1	2	3	4	5	6	7	8	9
E.M.B.E.R.	5	4	4	5	5	5	5	3	5
Firefighter	0	4	0	5	5	5	5	5	4
Hoser on a roof	0	4	5	5	3	4	5	4	4
Leave sprinkler on	3	4	3	5	4	5	5	4	5
WASP	5	4	4	4	4	3	4	3	4
Column #	1	2	3	4	5	6	7	8	9

C. Ideation Session Results

Mounting & Gimbal	Nozzles & Fluids	Camera & Mechatronics	Packaging	Miscellaneous
Staked in-ground	Nozzle angle	Number of cameras?	Flame-resistant	Multiple systems
Stakes & plate	Flowrate adjustment	One camera	Heat-resistant	Quadrant of smoke detectors
Leveling bubble	Nozzle angle default at 45 degrees; adjust to needed	Two cameras	All fits into pelican case	Remote-controller capacity
Auto-leveling	Full range; "rain down"	Imaging camera type	Plastic v. metal?	Warranty
Moving	Triggers homeowner's sprinkler system	Range of camera specified	Run off of Arduino	Water yard before?
Roof of house	Tubing system	Negate "wrong target" problems	Fan and hole in the bottom/mouth allowing heat to escape	After first ember, the danger is already there.
Maximize range	Waterproof from itself	Research further into blackbody radiation	Layering system	Init state that waters the yard initially.
Sprinkler on a Plate	Nozzle height above ground	Cameras all around		Should it aim or spray whole yard? If it sprays the whole yard it could prevent future flare-ups.
	Top & bottom nozzle idea	Cameras fixed		
	What Reynolds number is most effective?	Rotating nozzle		
	Minimize minor/major losses	Cameras set up around the yard		
	Find flowrate and average losses of common hose; set as standard for model	Camera resolution?		
	Attach hose when needed	Motor driver		
	Hose directly to base, or adapter?	Motors?		
	Own line for hose.	Stepper motors		
	Width/shape of stream	Servos		
	Mist is effective	Arduino/Microcontroller?		
	Water stops fire from re-lighting.	Backup Battery		
	Component of motion powered by hydraulic forces	How many batteries?		
	Soak, then go out	Roving mode		
	Don't waste water, though	Battery life balancing: performance vs. mechatronic complexity		
		Solar panel		
		Net-zero/net-positive in roving mode		
		Current and voltage?		
		On switch? Or always in roving mode?		
		Phone app?		

D. Decision Matrices

Pugh Matrices

Function: Fire Detection		Alternatives					
Criteria	Weight	Flir Lepton	Total	Seek Thermal	Total	Temperature Gun	Total
Cost	3	1	3	2	6	5	15
Distance	2	5	10	3	6	3	6
Accuracy	4	5	20	4	16	1	4
Power Efficiency	1	3	3	2	2	4	4
	Final Total		36		30		29
	Rank	1		2		3	

Function: Water Dispersion		Alternatives					
Criteria	Weight	Oscillating Sprinkler	Total	Angled Nozzle	Total	360° Spray	Total
Cost	2	5	15	3	9	5	15
Distance	3	4	8	3	6	4	8
Accuracy	4	4	16	4	16	2	8
Low Consumption	1	3	3	5	5	1	1
	Final Total		42		36		32
	Rank	1		2		3	

Function: Motion		Alternatives					
Criteria	Weight	DC Motor	Total	AC Motor	Total	Stepper Motor	Total
Cost	2	3	9	3	9	3	9
Speed	3	4	8	4	8	4	8
Accuracy	1	4	16	4	16	4	16
Power Efficiency	4	4	4	3	3	2	2
	Final Total		37		36		35
	Rank	1		2		3	

Function: Electronics		Alternatives					
Criteria	Weight	Raspberry Pi	Total	Arduino	Total	STM32	Total
Cost	4	4	12	4	12	3	9
Ease of Use	2	5	10	5	10	4	8
Memory	1	5	20	4	16	4	16
Power Efficiency	3	3	3	4	4	4	4
	Final Total		45		42		37
	Rank	1		2		3	

Weighted Decision Matrix

Morphological Matrix			
Fire Detection	Flir Lepton	Seek Thermal	Temperature Gun
Water Dispersion	Oscillating Sprinkler	Angled Nozzle	360° Spray
Motion	DC Motor	AC Motor	Stepper Motor
Electronics	Raspberry Pi	Arduino	STM32

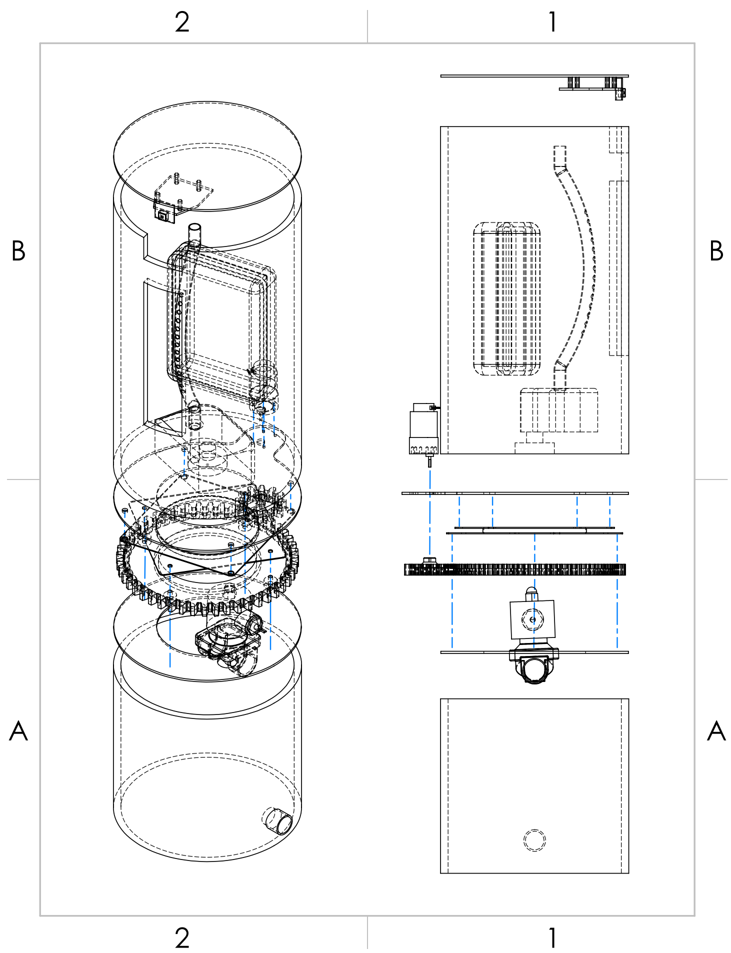
Criteria	Weight	Flir Lepton, Oscillating Sprinkler, DC Motor, Raspberry Pi		Seek Thermal, Oscillating Sprinkler, DC Motor, Arduino		Flir Lepton, Angled Nozzle, Stepper Motor, Arduino		Seek Thermal, Angled Nozzle, Stepper Motor, STM32		Flir Lepton, Oscillating Sprinkler, Stepper Motor, STM32	
		Score	Total	Score	Total	Score	Total	Score	Total	Score	Total
Cost	5	3	15	4	20	1	5	2	10	3	15
Coverage Area	2	5	10	5	10	2	4	2	4	5	10
Accuracy	4	4	16	4	16	5	20	5	20	4	16
Efficiency	3	5	15	4	12	2	6	3	9	3	9
Capacity	1	4	4	3	3	5	5	4	4	3	3
	Total	60		61		40		47		53	

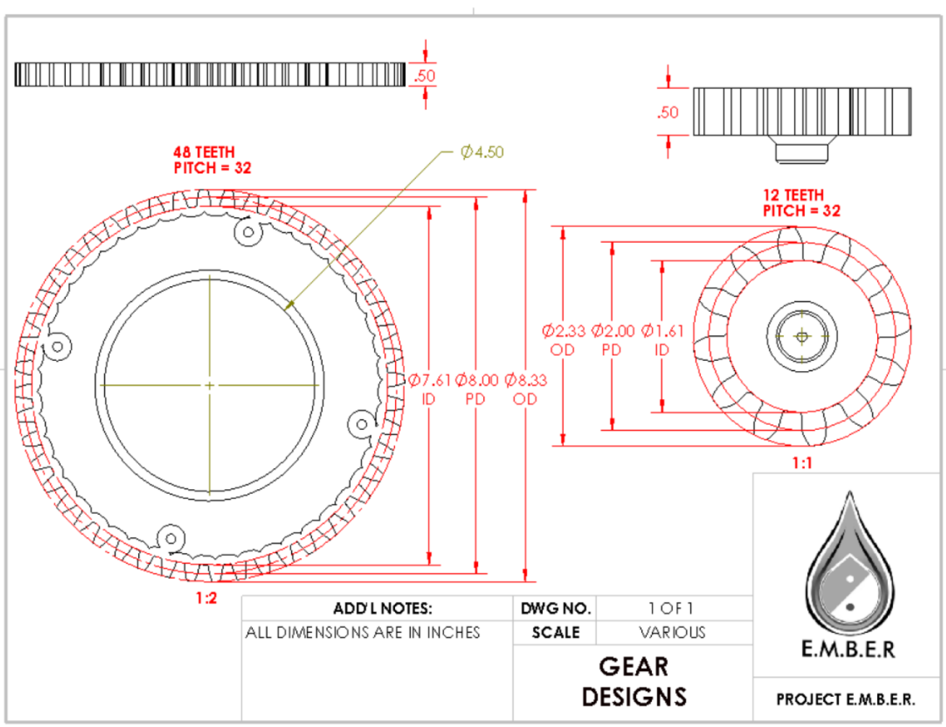
E. Drawing Package

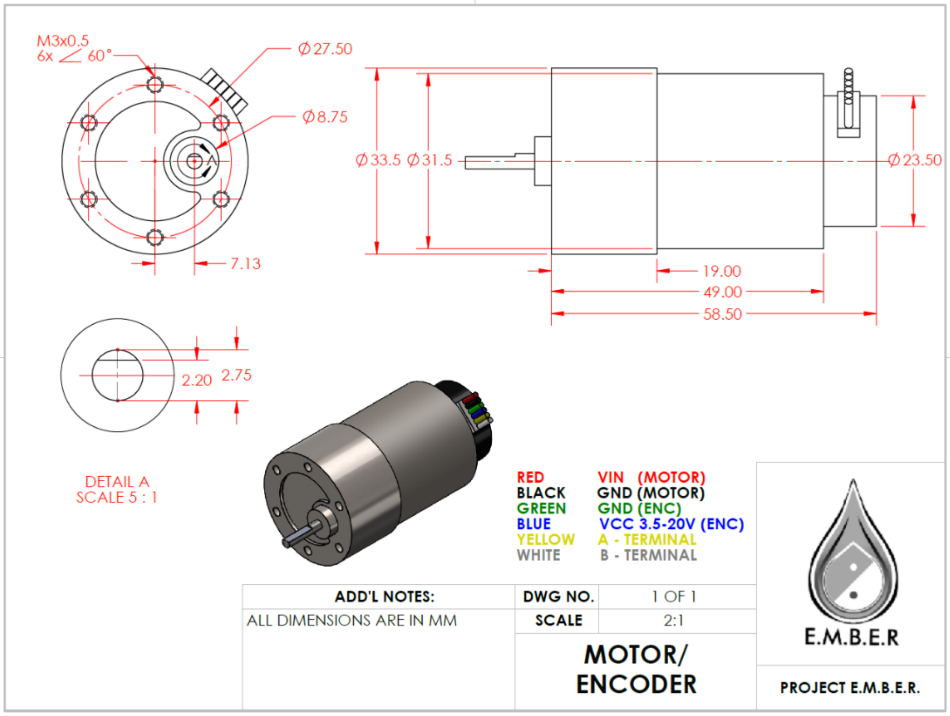
Indented Bill of Materials

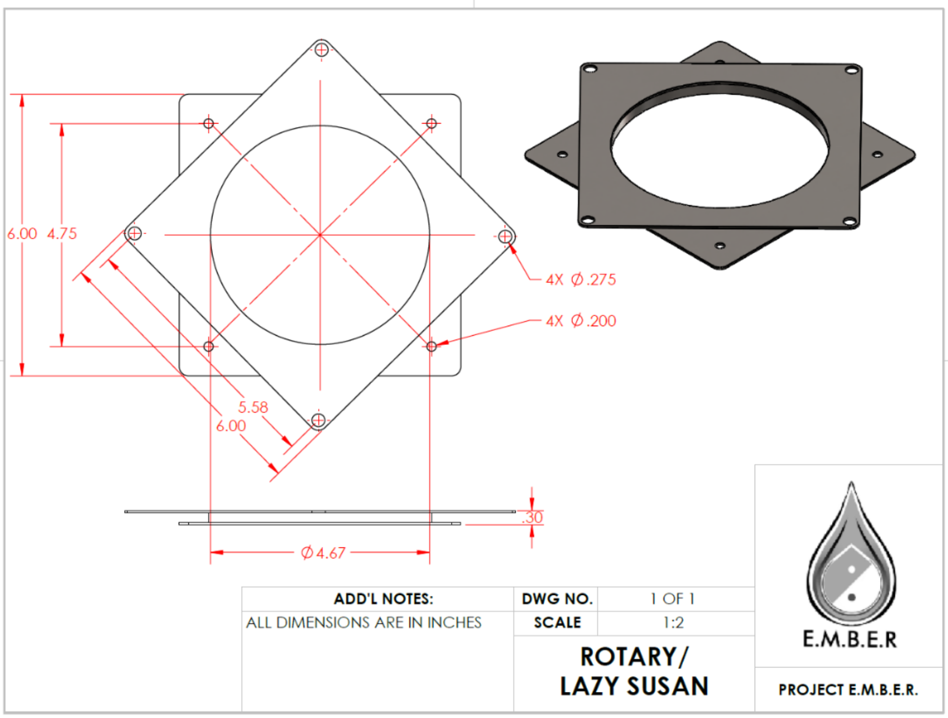
E.M.B.E.R.

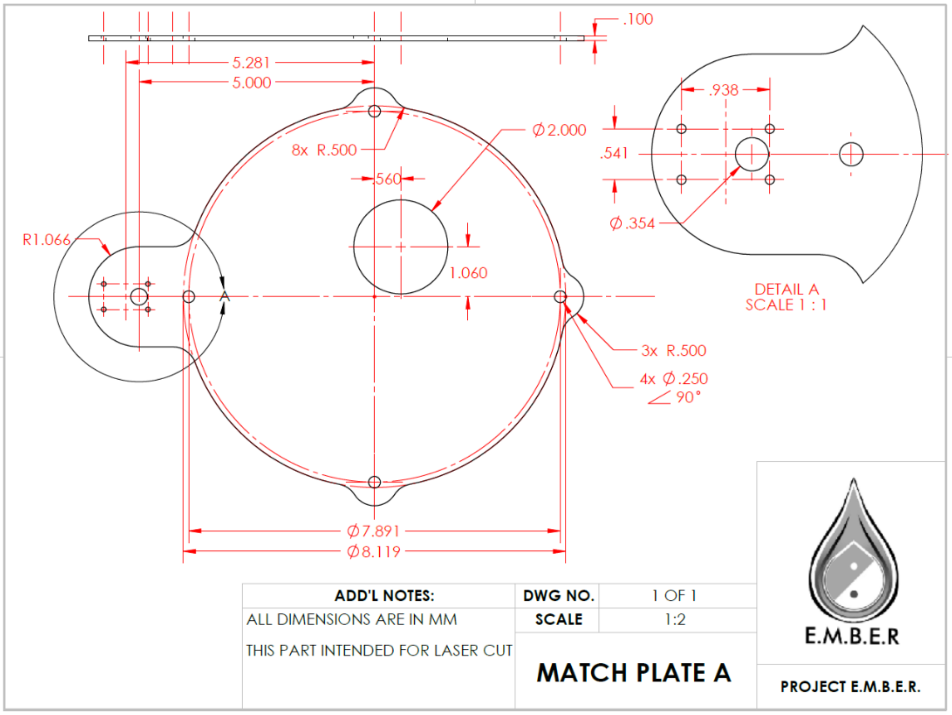
Assem. Level	Part Number	Description & Level	Vendor	Qty	Cost	Σ Cost
		0 / 1 / 2 / 3 / ...				
0	100000	Final Assembly				
1	101000	Top Assembly				
2	101001	8-inch PVC Pipe, 6 feet	Farm Supply	1	$ 55.00	$ 55.00
2	101002	Oscillating Sprinkler	Amazon	1	$ 8.60	$ 8.60
2	101010	Electronics Assembly				
3	101011	Raspberry Pi	Adafruit	1	$ 50.00	$ 50.00
3	101012	Lepton Camera	Digi-Key	1	$ 70.00	$ 70.00
3	101013	Lepton Breakout Board	Digi-Key	1	$ 39.99	$ 39.99
3	101014	Pelican Case	Amazon	1	$ 15.00	$ 15.00
1	102000	Rotational Assembly				
2	102001	Spur Gear	Manufactured	2	------	------
2	102002	Lazy Susan	Home Depot	1	$ 4.48	$ 4.48
2	102003	DC Motor with Encoder	Robot Shop	1	$ 29.00	$ 29.00
2	102004	Acrylic Mounting Plate	Manufactured	1	$ 10.00	$ 10.00
1	103000	Base Assembly				
2	103001	8-inch PVC Pipe, 6 feet	Same as 101001	------	------	------
2	103002	1/2-inch Flexible Hose, 5 feet	Home Depot	1	$ 4.93	$ 4.93
2	103003	Pipe Coupling	Home Depot	5	$ 1.50	$ 7.50
2	103004	Electric Solenoid Valve	Amazon	1	$ 32.00	$ 32.00
2	103005	Metal Stakes (4 pack)	Home Depot	1	$ 3.98	$ 3.98
	Total Parts			**19**		**$ 330.48**

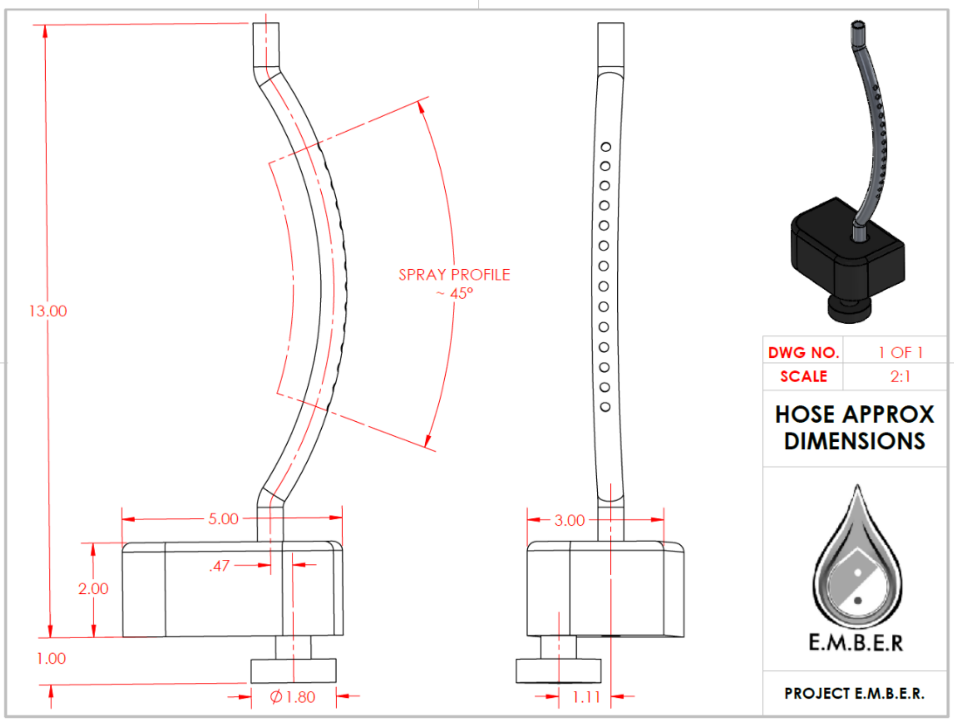

2
1
B
B
A
A
2
1


.50
.50
48 TEETH
PITCH = 32
Ø4.50
12 TEETH
PITCH = 32
Ø2.33 OD
Ø2.00 PD
Ø1.61 ID
Ø7.61 ID
Ø8.00 PD
Ø8.33 OD
1:1
1:2
ADD'L NOTES:
ALL DIMENSIONS ARE IN INCHES
DWG NO.
1 OF 1
SCALE
VARIOUS
GEAR DESIGNS
E.M.B.E.R
PROJECT E.M.B.E.R.


M3x0.5
6x 60°
Ø27.50
Ø8.75
Ø33.5 Ø31.5
Ø23.50
7.13
19.00
49.00
58.50
2.20 2.75
DETAIL A
SCALE 5 : 1
RED VIN (MOTOR)
BLACK GND (MOTOR)
GREEN GND (ENC)
BLUE VCC 3.5-20V (ENC)
YELLOW A - TERMINAL
WHITE B - TERMINAL
ADD'L NOTES:
ALL DIMENSIONS ARE IN MM
DWG NO. 1 OF 1
SCALE 2:1
MOTOR/
ENCODER
E.M.B.E.R
PROJECT E.M.B.E.R.


6.00 4.75
4X Ø.275
4X Ø.200
5.58
6.00
.30
Ø4.67
ADD'L NOTES:
ALL DIMENSIONS ARE IN INCHES
DWG NO. 1 OF 1
SCALE 1:2
ROTARY/
LAZY SUSAN
E.M.B.E.R
PROJECT E.M.B.E.R.


.100
5.281
5.000
8x R.500
.560
Ø2.000
R1.066
1.060
A
.938
.541
Ø.354
DETAIL A
SCALE 1 : 1
3x R.500
4x Ø.250
∠ 90°
Ø7.891
Ø8.119
ADD'L NOTES:
ALL DIMENSIONS ARE IN MM
THIS PART INTENDED FOR LASER CUT
DWG NO. 1 OF 1
SCALE 1:2
MATCH PLATE A
E.M.B.E.R
PROJECT E.M.B.E.R.


13.00
SPRAY PROFILE
~ 45°
5.00
.47
2.00
1.00
Ø1.80
3.00
1.11
DWG NO. 1 OF 1
SCALE 2:1
HOSE APPROX DIMENSIONS
E.M.B.E.R
PROJECT E.M.B.E.R.

F. Software Code

emberCamera.py: uses the Lepton camera to take pictures and analyze data

```
import numpy as np
from pylepton.Lepton3 import Lepton3       # Lepton software

class Fire_Detect:
    def __init__(self):
        pass

    def take_pic(self, fire_limit=350):
        with Lepton3("/dev/spidev0.1") as cam:
            raw_temp,_ = cam.capture()      # take picture
        kelvin = raw_temp/100               # convert to Kelvin
        self.fire_limit = fire_limit        # set minimum fire temp.
        self.left = kelvin[:,0:75]          # left section of array
        self.center = kelvin[:,75:85]       # center section of array
        self.right = kelvin[:,85:160]       # right section of array
        if np.any([x > self.fire_limit for x in kelvin]):
            analyze_data = 1
        else:
            analyze_data = 0
        return analyze_data

    def analyze(self):
        if np.any([x > self.fire_limit for x in self.left]):
            # number of pixels in left section that see fire
            cellsL = (self.left>self.fire_limit).sum()
        else:
            cellsL = 0                      # no fire
        if np.any([x > self.fire_limit for x in self.right]):
            # number of pixels in right section that see fire
            cellsR = (self.right>self.fire_limit).sum()
        else:
            cellsR = 0                      # no fire
        if np.any([x > self.fire_limit for x in self.center]):
            # number of cells in center section that see fire
            cellsC = (self.center>self.fire_limit).sum()
        else:
            cellsC = 0                      # no fire
        return cellsL, cellsC, cellsR
```

emberOperation.py: uses data from the Lepton camera to control motor and valve

```
import emberCamera
from adafruit_motorkit import MotorKit
from time import sleep

TURN_LEFT = 0.6                       # motor duty cycle to turn left
TURN_RIGHT = -0.6                     # motor duty cycle to turn right
STOPPED = 0                           # motor duty cycle to stop
WATER_ON = 1                          # valve duty cycle to open
WATER_OFF = 0                         # valve duty cycle to close
CHECKING = 0                          # CHECKING state variable
WATER = 1                             # WATER state variable

kit = MotorKit()                      # initialize the motor
valve = MotorKit()                    # initialize the valve
cam = emberCamera.Fire_Detect()       # initialize the camera

kit.motor1.throttle = TURN_RIGHT      # start the motor right
valve.motor2.throttle = WATER_OFF     # start the valve closed

state = CHECKING                      # current state
turning_state = TURN_RIGHT            # current motor direction

def firefighting_task(state, turning_state):
    if state == CHECKING:             # if CHECKING state,
        kit.motor1.throttle = STOPPED # stop motor
        sleep(0.2)                    # wait 0.2 seconds
        val = cam.take_pic(350)       # take a picture
        if val == 0:                  # if no fire detected, rotate
            kit.motor1.throttle = turning_state
            sleep(0.2)                # wait 0.2 seconds
        else:                         # if fire detected,
            fire = cam.analyze()      # analyze camera data
            fire_left = fire[0]       # number of fire pixels left
            fire_center = fire[1]     # number of fire pixels center
            fire_right = fire[2]      # number of fire pixels right
            if fire_center >= 1:      # if fire center, stop motor
                kit.motor1.throttle = STOPPED
                state = WATER         # go to WATER state
            elif fire_left >= 1:      # if fire left, rotate left
                kit.motor1.throttle = TURN_LEFT
                turning_state = TURN_LEFT
                sleep(0.2)            # wait 0.2 seconds
            elif fire_right >= 1:     # if fire right, rotate right
                kit.motor1.throttle = TURN_RIGHT
                turning_state = TURN_RIGHT
                sleep(0.2)            # wait 0.2 seconds
```

```
    elif state == WATER:              # if WATER state,
        val = cam.take_pic(350)       # take a picture
        if val == 0:                  # if no fire detected, rotate
            kit.motor1.throttle = turning_state
            state = CHECKING          # go to CHECKING state
        else:                         # if fire detected,
            fire = cam.analyze()      # analyze camera data
            fire_center = fire[1]     # number of fire pixels center
            if fire_center >= 1:      # if fire center, open valve
                valve.motor2.throttle = WATER_ON
                sleep(10)             # wait 10 seconds
                valve.motor2.throttle = WATER_OFF
                sleep(1)              # wait 1 second
            else:                     # if no fire center, rotate
                kit.motor1.throttle = turning_state
                state = CHECKING      # go to CHECKING state
    return state, turning_state       # return state & motor direction

try:
    while True:                       # run task until ctrl-c pressed
       [state,turning_state] = firefighting_task(state,turning_state)
except KeyboardInterrupt:
    kit.motor1.throttle = STOPPED     # stop motor
    valve.motor2.throttle = WATER_OFF # close valve
```

emberEncoder.py: uses the encoder to track device rotation (not implemented)

```
from LS7366R import LS7366R as ENC

class EmberEncoder:
    def __init__(self):
        self.enc = ENC.LS7366R(0, 1000000, 4)
        self.MaxCount = 2797
        self.MaxRotations = 4

    def Read_Enc(self):
        self.ticks = self.enc.readCounter()
        self.angle = self.ticks*360/(self.MaxCount*self.MaxRotations)
        if self.ticks <= -self.MaxCount/4:
            low_limit = 1
            high_limit = 0
        elif self.ticks >= self.MaxCount*(self.MaxRotations + 1/4):
            high_limit = 1
            low_limit = 0
        else:
            low_limit = 0
            high_limit = 0
        return self.angle, low_limit, high_limit, self.ticks
```

G. Project Budget

Item	Item Description	Vendor	Vendor Model Number	Project Part Number	Purchase Method	Purchase Date	Arrival Date
8-inch diameter PVC pipe	Housing for the top and base of device	Farm Supply Company	N/A	101001 and 103001	By team	4/23/19	4/23/19
Melnor oscillating sprinkler	Sprinkler with verticle nozzle array	Amazon	20261	101002	By team	2/8/19	2/9/19
Raspberry Pi 3	Single-board computer	Amazon	B+	101011	Donation	N/A	N/A
FLIR Lepton camera	LWIR micro thermal camera module	FLIR	3.5	101012	Donation	4/22/19	4/26/29
FLIR Lepton breakout board	Printed circuit board for camera	FLIR	250-0587-00	101013	Donation	4/22/19	4/26/19
Pelican micro case	Insulated case for electronics	Amazon	1010	101014	By team	5/7/19	5/9/19
Spur gears	3D printed sun and planetary gears	Daniel Santoro	N/A	102001	Donation	5/2/19	5/2/19
Everbilt lazy-susan	Turntable for the rotational assembly	Home Depot	49548	102002	By team	4/20/19	4/20/19
DC motor with encoder	Motor for rotation of the top housing and encoder to track rotation	Robot Shop	RB-Dfr-444	102003	By team	10/17/19	10/25/19
Acrylic sheet	Plastic sheet for the laser cut motor mounting plate	Home Depot	MC-21	102004	By team	5/16/19	5/16/19
1/2-inch flexible hose	Hose between solenoid valve and sprinkler	Home Depot	702361	103002	By team	4/20/19	4/20/19
Pipe and hose adaptors	Connections between garden hose, solenoid valve, hose, and sprinkler	Home Depot	Multiple	103003	By team	4/20/19	4/20/19
Electric solenoid valve	Valve to control water flow	Amazon	USS2-00007	103004	By team	5/7/19	5/9/19
Metal stakes	Stakes to stabilize device	Home Depot	MSD-50	103005	By team	4/20/19	4/20/19
2-hole straps	Metal straps to secure sprinkler and valve	Home Depot	Multiple	N/A	By team	5/16/19	5/16/19

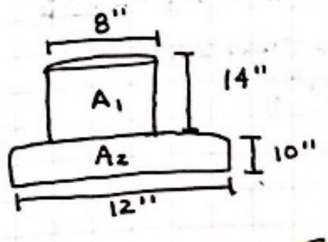
H. Gear, Motor, and Stake Analysis

4/3/19 — 39

Analysis:

Stake Analysis:

1) How many stakes?
2) Size of stakes?
3) Stake Material?



$A_1 = (\frac{8}{12} ft)(\frac{14}{12} ft) = 0.78 ft^2$

$A_2 = (\frac{10}{12} ft)(\frac{12}{12} ft) = 0.83 ft^2$

$A_{tot} = 1.61 ft^2$

$F_{wind} = F_{stakes} = F_D$

$F_{wind} = \frac{1}{2} \rho v^2 C_D A \qquad C_D \approx 1$

$F_{wind} = \frac{1}{2} \rho v^2 A$

Assume max wind speed of 40mph:

$\rho_{air} = 0.0765\ lb/ft^3$

$V_{wind} = 40mph = 58.7 \frac{ft}{s}$

$A = 1.61 ft^2$

$F_{wind} = \frac{1}{2}(0.0765 \frac{lb}{ft^3})(58.7 \frac{ft}{s})^2 (1.61 ft^2)$

$F_{wind} = 212.2 \frac{lb \cdot ft}{s^2} \left(\frac{lbf}{32.2 \frac{lb \cdot ft}{s^2}}\right)$

$F_{stakes} = \underline{F_{wind} = 6.59\ lbf}$ (for all stakes)

another way of approaching Fwind:

$P_{wind} = 0.00256 V^2 \Rightarrow$ Wind Pressure Eq. $\begin{cases} P\ [lbf/ft^3] \\ V\ [mph] \end{cases}$

$P_{wind} = 0.00256 (40mph)^2$

$P_{wind} = 4.096 \frac{lbf}{ft^2}$

$F_{wind} = P_{wind} A = (4.096 \frac{lbf}{ft^2})(1.61 ft^2)$

$F_{stakes} = \underline{F_{wind} = 6.61\ lbf}$ (for all stakes)

Stake Analysis Cont'd...

Found F_{stakes}, now look @ soil:

Typical Soil Density for Urban Lawns = $1.5-1.9\ \frac{g}{cm^3}$

(Source: Schueler, T. 2000. "The Compaction of Urban Soil: The Practice of Watershed Protection")

$\therefore\ \rho_{soil} = 1.5\ \frac{g}{cm^3} = 93.6\ \frac{lb}{ft^3}$

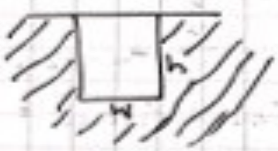
Dimensions of Stakes:

Use Pressure / Force on a submerged surface (in soil)

$P = \rho g h$

$(P = \frac{F}{A})$

$\therefore\ \frac{F}{A} = \rho g h$



$\frac{F}{hw} = \rho g h$

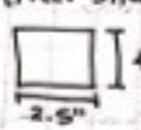
$* \boxed{h^2 w = \frac{F_{stake}}{\rho_{soil}\, g}}$

$F_{stake} = 6.61 lb_f \div 3\ stakes = 2.20\ lb_f/stake$

$h^2 w = \frac{2.20 lb_f\ (32.2\ \frac{lb_m ft}{s^2})}{(93.6\ \frac{lb}{ft^3})(32.2\ \frac{ft}{s^2})}$

$h^2 w = 0.0235 ft^3 = 40.6 in^3$

sq/rec. shape



$\begin{cases} h = 4" \\ w = 2.5" \end{cases}$

$(4in)^2(2.5in) = 40 in^3 \simeq 40.6 in^3$ ✓

rec. pyr. shape

$A = \frac{1}{2} hw$

$\therefore\ \frac{1}{2} h^2 w = 40.6 in^3$

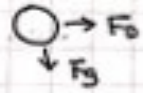
$\begin{cases} h = 5.5 in \\ w = 2.75 in\ (@\ base) \end{cases}$

$\frac{1}{2}(5.5in)^2(2.75in) = 41.6 in^3 > 40.6 in^3$ ✓

Stake Analysis Cont'd...

What would F_{stakes} have to be if a soccer ball hit the device @ 15mph ← dir. of motion

D = 8.65in (for typical soccer ball)



$A = \frac{\pi}{4}d^2 = \frac{\pi}{4}(8.65in)^2 = \underline{58.8in^2}$

$V = 15mph = \underline{22\ ft/s}$

$\rho_{air} = \underline{0.0765\ lb/ft^3}$

C_D (sphere) $= \underline{0.47}$

$F_D = \frac{1}{2}\rho v^2 C_D A$

$F_D = \frac{1}{2}(0.0765\ lb/ft^3)(22\ ft/s)^2(0.47)(58.8in^2)$

$\underline{F_D = 15.89\ lbf}$

$\therefore \underline{F_{stake} = 5.30\ lbf}$ /stake (assuming 3 stakes)

$h^2w = \frac{F_{stake}}{\rho_{soil}\ g}$

$h^2w = \frac{5.30\ lbf\ (32.2)}{(93.6\ \frac{lb}{ft^3})(32.2\ \frac{ft}{s^2})}$

$h^2w = 0.0566\ ft^3 = \underline{97.8in^3}$

look @ Valley View Industries Metal Stakes @ Home Depot (could work well) * ⇐ $\begin{cases} h = 9in \\ w = 1.25in \end{cases}$

$(9^2 in)(1.25in) = 101.25in > 97.8in^3$ ✓

Stake Material:

Steel – $\rho_{steel} = 0.280 - 0.291\ lb/in^3$

if used sq. pyramaid $h = 5.5in$, $w = 2.75in$ (last pg.)

$V = w^2\frac{h}{3} = \frac{1}{3}(2.75in)^2(5.5in) = \underline{13.86in^3}$

$m = \rho V = (0.280\ \frac{lb}{in^3})(13.86in^3) = \boxed{3.88lb\ /stake}$

Aluminum – $\rho_{aluminum} = 0.1\ lb/in^3$

$V = 13.86in^3$

$m = \rho V = (0.1\ \frac{lb}{in^3})(13.86in^3) = \boxed{1.39\ lb\ /stake}$

5/5/19

Stake Analysis Cont'd:

How high of a wind speed can our device withstand?

Dimensions of Stakes: 9" × 1"

$\rho_{soil} = 93.6\ lb/ft^3$

from page 40

$$h^2 w = \frac{F_{stake}}{\rho_{soil}\, g}$$

$$F_{stake} = \left(\frac{9}{12} ft\right)^2 \left(\frac{1}{12} ft\right)\left(93.6 \frac{lb}{ft^3}\right)\left(32.2 \frac{ft}{s^2}\right)\left(\frac{1}{32.2}\right)$$

(per stake) $F_{stake} = 4.39\ lbf = F_{wind}$

$$F_{stake} = 3(4.39\ lbf) = 13.17\ lbf$$

$$P_{wind} = 0.00256 V^2$$

$$\frac{F_{wind}}{A} = 0.00256 V^2$$

$$V^2 = \frac{13.17\ lbf}{(1.61 ft^2)(0.00256)}$$

V = 56.5 mph

max wind velocity before stakes can't support device & device tips.

4/5/19

Gear/Motor Analysis

Top housing rotational speed: (estimate) $\omega = \frac{1\,rev}{60\,sec} \times \frac{2\pi\,rad}{rev} = 0.105\ rad/s$

$\omega_{min} = 0.105 \frac{rad}{s}$

$\omega_{max} = 0.209\ rad/s$

Torque constant of the motor: $K_T = \frac{\text{rated/nominal voltage}}{\text{no-load speed}}$ $\left[V\text{-}s \text{ or } \frac{N\text{-}m}{A}\right]$

Max motor torque: $T_{max} = \frac{V \cdot K_T}{R}$ @ rated voltage w/ 100% duty

For 3D printed gears: $\phi = 25°$ (pressure angle)

max recommended gear ratio = 5

minimum # of teeth on pinion = 11

For $N_P = 12$, gear ratio = 5, $N_G = 60$ teeth: $P = 7.5$ (high)

$d_G = 8$ inches and $d_P = 1.6$ inches

* Analysis tool in excel for further adjustment *

$K_T = \frac{20V}{59 \frac{rad}{s}} = 0.339\ V\text{-}S$

$T_{output} = 2.05\,N\text{-}m(5) = 10.26\ N\text{-}m$

$T_{max} = \frac{20V(0.339)V\text{-}s}{3.3\Omega} = 2.05\ N\text{-}m$

I. Failure Modes and Effects Analysis

System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurence	Current Detection Activities	Detection	Priority	Recommended Action(s)	Responsibility & Target Completion Date	Action Results: Actions Taken	Action Results: Severity	Action Results: Occurence	Action Results: Criticality
Stationary Base/Provide Stability	Base tips over	Device fails to work	8	1) Poor stake geometry/integrity 2) Extreme weather conditions 3) Top housing rotating imbalance	Stake analysis: geometry, stress, and fatigue	2	Test various stake materials and lengths	6	96	Ensure stake material and geometry is acceptable	Chris Slezak	Stake material and geometry are acceptable	8	2	Mediu m
Stationary Base/Protect Piping, and Valve	Base cracks/breaks and starts to leak in water	a) Sharp edges exposed b) Fire hazard with water coming into contact with electronics	10	1) Impact from external object 2) Base material too brittle and suseptable to cracking	Base material analysis: stress and fatigue	3	Test impact resistance of base material	9	270	Maximize base stability and water resistance	Danny Santoro	Base stability was maximized	10	3	Critical
Sprinkler/Spray Water at Fire	Sprinkler doesn't spray water when directed	Device doesn't extinguish fire	8	1) Clogged nozzles 2) Valve does not open 3) Clogged pipe 4) Kinked garden hose	1) Pipe deflection analysis 2) Valve pressure analysis	2	Test valve actuation at maximum pressure	4	64	Ensure valve functionality	Chris Slezak	Valve is fully functional	8	2	Mediu m
Sprinkler/Conserve Water	Sprinkler fails to stop spraying water at time intervals set	Sprinkler uses an unnecessary amount of water	5	1) Valve does not close 2) Camera detects a fire when there isn't one	1) Valve pressure analysis 2) Camera temperature detection analysis	5	Test thermal camera temperature range	3	75	Calibrate valve and camera software	Danny Santoro	Valve and camera software was calibrated	5	5	High
Top Housing/Rotate Camera and Sprinkler	Top doesn't rotate	Device's range of motion is limited	7	1) Broken gear teeth 2) Disconnected wire 3) Motor shorted due to moisture 4) Broken bearing 5) Dead battery	1) Water resistance 2) Bearing and gear stress analysis	6	Test battery life and water resistance of motor	4	168	Ensure wires and tubing do not get twisted during rotation	Kylie Fernandez	Wires and tubing are not twisted during limited rotation	7	6	High
Top Housing/Provide Stability	Rotating imbalance	Wears down quicker than if balanced	6	1) Gear shafts not aligned 2) Weight not well-distributed in top housing	1) Gear/motor testing 2) Balance weight around the housing axis of rotation	2	Check alignment of gear shafts and weight distribution	8	96	Minimize gear interference	Ryan Kissinger	Gear interference was minimized	6	2	Mediu m
Top Housing/Protect Camera, Sprinkler, and Electronics	Top breaks/cracks and allows moisture into electronics	a) Sharp edges exposed b) Fire hazard with water coming into contact with electronics c) Functionality and mobility of device decreases	10	1) Impact from external object 2) Housing material too brittle and suseptable to cracking	Housing material analysis: stress and fatigue	3	Test impact resistance of housing material	9	270	Maximize top stability and water resistance	Kylie Fernandez	Top stability was maximized	10	3	Critical
General/Hold Parts Together	Wears down over time	a) Useful life decreases b) Performance decreases c) Potential failure	6	1) Piping comes loose 2) Wires come loose 3) Top housing and base rub together	1) Proper pipe/coupling sizes 2) Proper wire length and location 3) Balanced rotation	5	Test strength of couplings and wire connections	3	90	Ensure all connectors and fasteners are secure	Danny Santoro	All connectors and fasteners are secure	6	5	Mediu m
General/Maintain Appearance	Wears down over time	a) Device loses original appearance b) Desirability decreases	3	1) Environmental conditions 2) Fatigue	1) No exposed wires 2) External surface finish ideal for outdoor exposure	2	Examine features for optimal appearance	10	60	Maintain device aesthetic	Ryan Kissinger	Device aesthetic was maintained	3	2	Low

J. Design Hazard Checklist

DESIGN HAZARD CHECKLIST

Team: E.M.B.E.R. Advisor: Ridgely Date: 5/5/19

Y	N	
☑	☐	1. Will the system include hazardous revolving, running, rolling, or mixing actions?
☐	☑	2. Will the system include hazardous reciprocating, shearing, punching, pressing, squeezing, drawing, or cutting actions?
☑	☐	3. Will any part of the design undergo high accelerations/decelerations?
☐	☑	4. Will the system have any large (>5 kg) moving masses or large (>250 N) forces?
☐	☑	5. Could the system produce a projectile?
☐	☑	6. Could the system fall (due to gravity), creating injury?
☐	☑	7. Will a user be exposed to overhanging weights as part of the design?
☑	☐	8. Will the system have any burrs, sharp edges, shear points, or pinch points?
☐	☑	9. Will any part of the electrical systems not be grounded?
☐	☑	10. Will there be any large batteries (over 30 V)?
☐	☑	11. Will there be any exposed electrical connections in the system (over 40 V)?
☐	☑	12. Will there be any stored energy in the system such as flywheels, hanging weights or pressurized fluids/gases?
☐	☑	13. Will there be any explosive or flammable liquids, gases, or small particle fuel as part of the system?
☐	☑	14. Will the user be required to exert any abnormal effort or experience any abnormal physical posture during the use of the design?
☐	☑	15. Will there be any materials known to be hazardous to humans involved in either the design or its manufacturing?
☐	☑	16. Could the system generate high levels (>90 dBA) of noise?
☑	☐	17. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, or cold/high temperatures, during normal use?
☐	☑	18. Is it possible for the system to be used in an unsafe manner?
☐	☑	19. For powered systems, is there an emergency stop button?
☐	☑	20. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
The system includes revolving components and gears.	Enclose the gears to prevent human fingers from fitting inside.	10/15/19	10/10/19
The system has a revolving top housing that accelerates and decelerates quickly.	Run the DC motor with a duty cycle of 60% to ensure the angular acceleration and torque do not exceed an unsafe amount.	10/3/19	10/1/19
The system has pinch points in the rotating gear mesh.	Enclose the gears to prevent human fingers from fitting inside and keep the nozzle window small to avoid pinching fingers.	10/15/19	10/10/19
The system will be exposed to potentially extreme environmental conditions because it is intended to be left outdoors year-round and in range of wildfires.	Build a housing from appropriate materials to insulate the device from environmental conditions and heat.	6/6/19	5/28/19

K. Risk Assessment

Risk Scoring System: ANSI B11.0 (TR3) Two Factor

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level
1-1-1	operator(s) connect garden hose	pressure : leakages leaked water	Minor Likely	Low		Minor	
1-2-1	operator(s) turn on power	electrical / electronic : normally live parts(direct contact) exposed wiring	Moderate Unlikely	Low		Moderate	
1-2-2	operator(s) turn on power	electrical / electronic : water / wet locations leaked water	Catastrophic Unlikely	Medium		Catastrophic	
1-2-3	operator(s) turn on power	electrical / electronic : unexpected start up faulty power switch	Moderate Unlikely	Low		Moderate	
1-2-4	operator(s) turn on power	electrical / electronic : software errors faulty program	Serious Remote	Low		Serious	
1-2-5	operator(s) turn on power	pressure : fluid ejection faulty camera	Moderate Likely	Medium		Moderate	
1-3-1	operator(s) stake into ground	mechanical : stabbing / puncture sharp stake	Serious Unlikely	Medium		Serious	
1-3-2	operator(s) stake into ground	ergonomics / human factors : excessive exertion hard ground	Moderate Remote	Negligible		Moderate	
2-1-1	engineer(s) connect power	electrical / electronic : normally live parts(direct contact) exposed wiring	Catastrophic Remote	Low		Catastrophic	
2-1-2	engineer(s) connect power	electrical / electronic : electrostatic / arcing / sparking improper connection	Serious Remote	Low		Serious	
2-1-3	engineer(s) connect power	electrical / electronic : water / wet locations leaked water	Serious Unlikely	Medium		Serious	
2-1-4	engineer(s) connect power	fire and explosives : smoke incorrect wiring	Serious Remote	Low		Serious	
2-2-1	engineer(s) run software program	electrical / electronic : software errors faulty program	Serious Unlikely	Medium		Serious	
2-3-1	engineer(s) connect garden hose	pressure : leakages leaked water	Minor Likely	Low		Minor	
3-1-1	passer-by / non-user walk near device	slips / trips / falls : trip device unnoticed	Moderate Remote	Negligible		Moderate	
3-1-2	passer-by / non-user walk near device	pressure : fluid ejection false camera reading	Serious Unlikely	Medium		Serious	
3-2-1	passer-by / non-user touch device	pinch points : between gear/housing improper shield	Moderate Unlikely	Low		Moderate	
3-2-2	passer-by / non-user touch device	electrical / electronic : normally live parts(direct contact) exposed wiring	Serious Remote	Low		Serious	

L. Operators' Manual

Congrats on purchasing a wildfire self-insurance device! Please follow the steps below to get set up.

1. Remove the device from the packaging and take outside to the area being protected.
    a. The device is capable of protecting a circular area 50 feet in diameter.
    b. Multiple devices may be used in conjunction to increase the protected area.

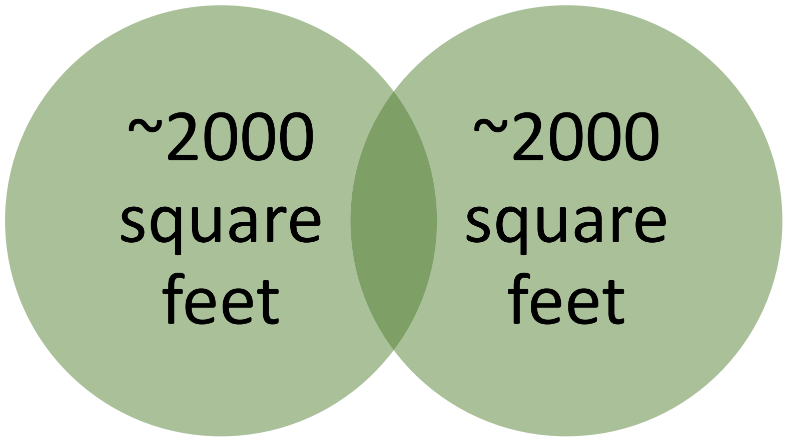


Figure L-1. Example of protected area with two devices.

2. To install the device, use the three stakes coming out of the base to press into the ground at the center of the protected area. Push down on the top of the device until the base is flush with the ground.

Figure L-2. Base and three stakes.

3. Charge the device by plugging a power cord into the USB connector positioned above the motor. *Use an extension cord if necessary*.

Figure L-3. Power connector and switch above motor.

4. The device is fully charged when the five green lights above the connector is on.
5. To supply water to the device, connect a garden hose to the adaptor extending out of the base of the device. *Not necessary to open the hose spigot at this time.*

Figure L-4. Garden hose adaptor in base.

6. During a wildfire evacuation, supply water to the device by opening the garden hose spigot. Then, turn the device on by switching the power button above the motor to on.

Keep the device charged and garden hose connected at all times to make evacuation faster, and therefore safer.

M. Design Verification Plan & Report

Senior Project DVP&R

Date: 11/20/2019	Team: E.M.B.E.R.	Sponsor: Dr. Richard Emberley	Description of System: Automated Wildfire Home Protection Device	DVP&R Engineers: Daniel Santoro, Kylie Fernandez, Chris Slezak, Ryan Kissinger

TEST PLAN										TEST REPORT			
Item No.	Specification #	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES		TIMING		TEST RESULTS			NOTES
						Quantity	Type	Start date	Finish date	Test Result	Quantity Pass	Quantity Fail	
1	1	Weight	Under 20 pounds	Everyone	FP	3	Sys	11/9/19	11/9/19	17.9 pounds	3	0	
2	2	Water Resistance	Up to IPX 5	Everyone	SP	2	Sub	TBD	TBD				
3	4 and 8	Coverage Area/Weather Resistance	Radius of 25 feet	Everyone	SP	10	Sub	11/9/19	11/9/19	25 feet	10	0	Use anemometer
4	5	Accuracy	Within one foot	Everyone	FP	3	Sys	11/16/19	11/16/19	4 inches	3	0	
5	6 and 7	Set Up Time/User Complexity	Under 15 minutes	Everyone	FP	4	Sys	11/21/19	11/21/19	5 minutes	2	0	More participants
6	9	Fire Detection	5-in. dia. at 25 feet	Everyone	SP	75	C	10/9/19	10/9/19	5-in. at 30 feet	70	5	

N. Test Procedures

Test #1: Weight

Description: The following test measures the weight of the device to determine whether the weight specification is met. This test is run after the device is completed.

Location: The test takes place on a standard bathroom scale.

Equipment:

- Completed device
- Standard scale

Safety Procedure: The team takes care not to drop the device while testing.

Data Collection: The device is weighed 3 times and the average weight is calculated.

Test #2: Water Resistance

Description: The following test measures water resistance of the device up to the specification of IPX 5. This test follows a modified version of the IPX 5 water resistance standard. The Pelican case for the electronics and fluid hose connections are evaluated.

Location: The test takes place near a water spigot.

Equipment:

- Device without electronics
- Pelican case
- Garden hose
- Stopwatch
- Tape measure
- Water spigot

Safety Procedure: All electronics are removed from the Pelican case prior to testing to ensure their protection in the event the case leaks.

Data Collection: The Pelican case is sprayed from all angles for 15 minutes at a distance of 10 feet by a garden hose with standard house pressure, 60 psi. The Pelican case is visually inspected for leaks. Additionally, the same hose is connected to the device, and water runs through the valve and out of the sprinkler for 15 minutes. A visual inspection of the fluid hose connections at full pressure is conducted to detect leaks.

Test #3: Coverage Area/Weather Resistance

Description: The following test measures the coverage area of water from the device and investigates the effect of wind on this coverage area.

Location: The test takes place near a water spigot.

Equipment:

- Device without electronics
- Anemometer
- Tape measure
- Garden hose
- Water spigot

Safety Procedure: All electronics are removed from the device prior to testing to ensure their protection.

Data Collection: The device is set up in an open area and connected to a garden hose with the water spigot and valve open. The nominal coverage area of water from the device is measured during a period of low wind, < 4 mph. This is accomplished by measuring the spray distance which represents the radius of said area. Next, the device is tested during various wind speeds measured by the anemometer. The measurement of spray distance is repeated and recorded with wind speed 10 times, or until a satisfactory performance curve is developed.

Test #4: Accuracy

Description: The following test determines if the accuracy of the device meets the specification of targeting within 1 foot. This test evaluates the device as a whole because its fire detecting and fire extinguishing capabilities are combined.

Location: The test takes place near a water spigot and metal fire pit.

Equipment:

- Completed device
- Laptop
- Paper towels
- Lighter
- Fire pit
- Tape measure
- Garden hose
- Water spigot

Safety Procedure: The fire is kept small and contained in the metal fire pit with a lid at all times.

Data Collection: The device is positioned 15 feet from the fire pit and connected to a garden hose with the water spigot open. Paper towels are placed in the fire pit and ignited. A laptop is used to run the Raspberry Pi and begin the firefighting software. When the device targets the fire, the valve open for 10 seconds. The distance from the center of the spray to the center of the fire is measured. This process is repeated three times, and the average standard deviation of the water from the fire is calculated.

Test #5: Set Up Time/User Complexity

Description: The following test measures the time it takes for a person to get the device up and running, as well as evaluates the complexity of the process.

Location: Outdoors

Equipment:

- Completed device
- Garden hose
- Stopwatch

Safety Procedure: Neither water nor power are utilized during this test.

Data Collection: A sample of 4 people are gathered for the test. The time is takes them each to unbox, set up, and connect the device to a hose is measured. The time starts when they touch the box and ends when they are ready to turn on the power switch. Participants do not watch the others complete the test. They are asked to assess the difficulty of the process on a scale of 1 to 5.

Test #6: Fire Detection

Description: The following test evaluates the ability of the Lepton thermal camera to detect spot fires at distances up to 25 feet. The fire in a 5-inch tray simulates a spot fire which is compared to the predicted detection of 5 pixels at 25 feet from the camera.

Location: Cal Poly 13-126 Engine Laboratory

Equipment:

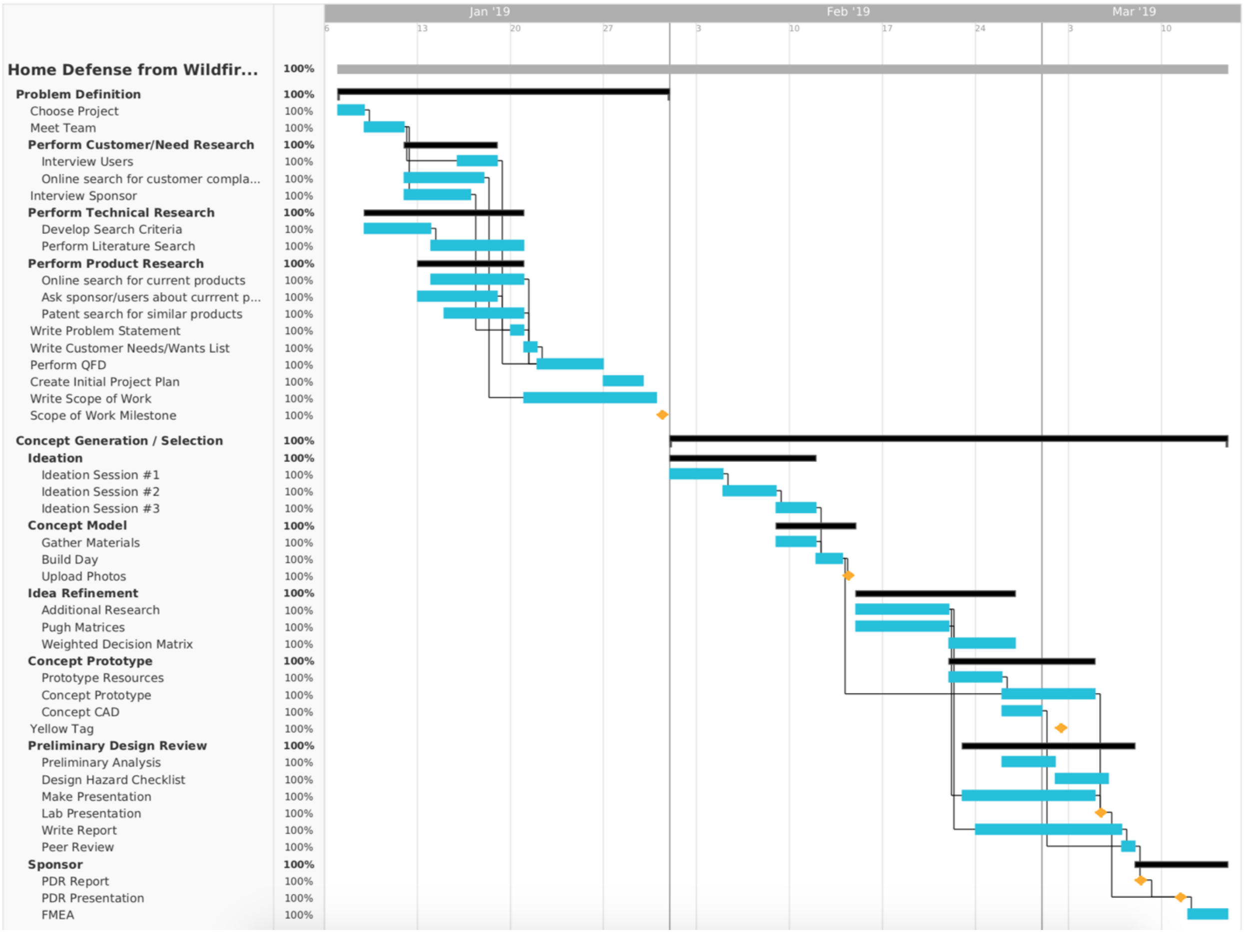
- Lepton thermal camera
- Raspberry Pi
- Laptop
- Pine needles and leaves
- 5-inch diameter metal tray
- Lighter
- Tape measure

Safety Procedure: The test is performed under a fume hood with Dr. Richard Emberley's supervision. A fire extinguisher is present in case of emergencies.

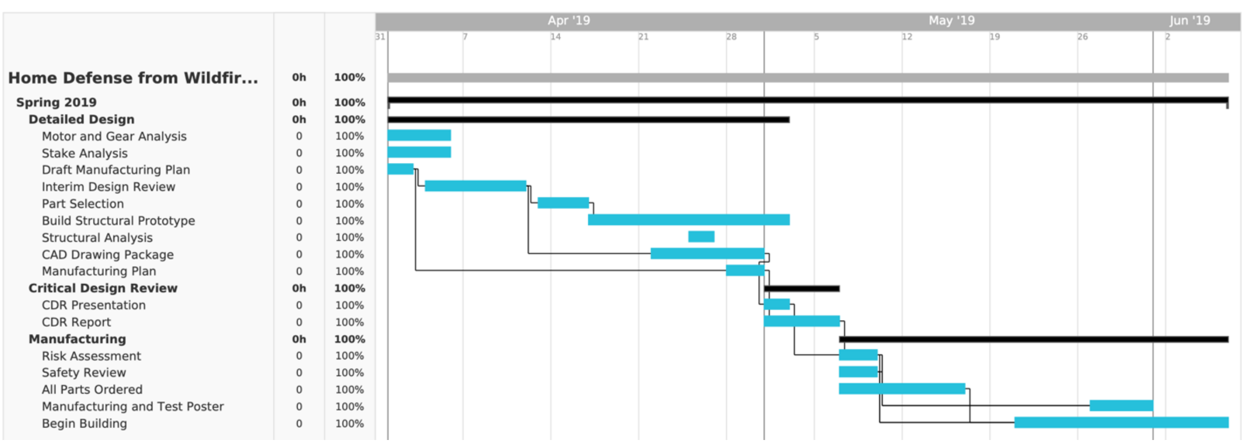
Data Collection: Pine needles and leaves are collected and placed into the small metal tray under the fume hood. The Lepton camera is set up 5 feet from the tray. A laptop is used to run the Raspberry Pi and take a picture every 1 second. After the fire is ignited, the Lepton camera takes thermal images of the fire for at least 15 seconds. This picture-taking process is repeated at 10, 15, 20, and 25 feet from the tray. The thermal data is analyzed to determine the number of pixels seeing temperatures greater than 350 degrees Kelvin.

O. Gantt Chart

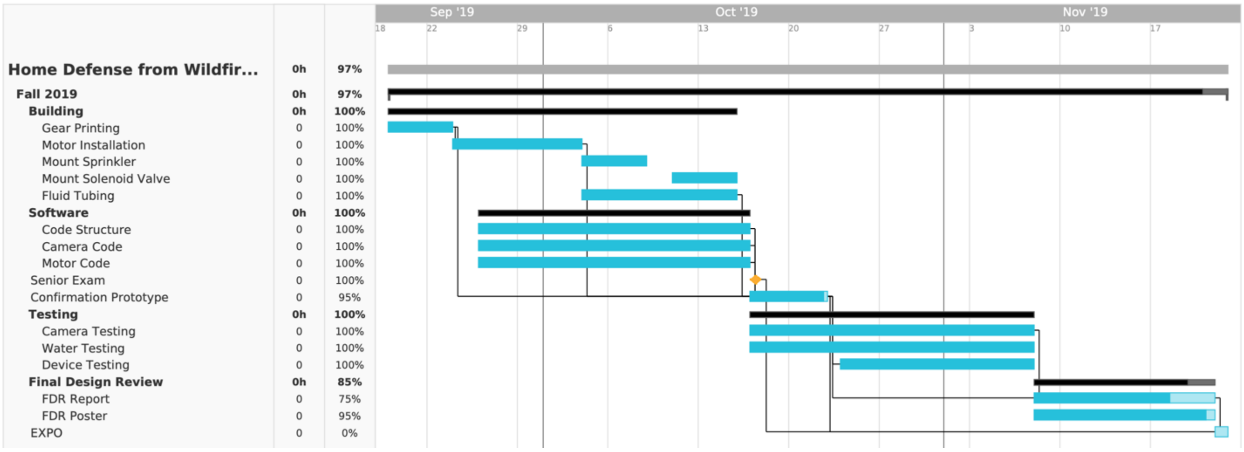
Winter 2019



Spring 2019



Fall 2019


Sep '19
Oct '19
Nov '19
18
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17
Home Defense from Wildfir... 0h 97%
Fall 2019 0h 97%
Building 0h 100%
Gear Printing 0 100%
Motor Installation 0 100%
Mount Sprinkler 0 100%
Mount Solenoid Valve 0 100%
Fluid Tubing 0 100%
Software 0h 100%
Code Structure 0 100%
Camera Code 0 100%
Motor Code 0 100%
Senior Exam 0 100%
Confirmation Prototype 0 95%
Testing 0h 100%
Camera Testing 0 100%
Water Testing 0 100%
Device Testing 0 100%
Final Design Review 0h 85%
FDR Report 0 75%
FDR Poster 0 95%
EXPO 0 0%