1.0 Introduction and Background

1.1 General background

Wildfires are a common and natural event in California, usually near the end of dry and long summers. However, as a result of climate change California is becoming hotter and drier than ever before. Recently the state has suffered long droughts and record temperatures as high as 79.7 degrees Fahrenheit in July 2018, which are ideal conditions for wildfires to begin and spread [1].

Furthermore, a 2017 study concluded that 15% (over two million) of California's homes are located in high or extremely high-risk zones, while another 12% are in moderate risk areas [2]. Thus, over a quarter of the homes in California are at risk of being damaged by an annual wildfire. In addition to the lives at risk, wildfires are extremely expensive. The Camp and Woolsey wildfires of 2018 alone covered over 200,000 acres, resulting in damage estimates of over $19 billion [3]. Firefighting costs have also more than tripled from $242 million in the fiscal year of 2013 to $773 million in the fiscal year of 2018 [4].

In addition, climate models predict an increase in droughts and wildfires for the state of California. An assessment written by the state predicts California may see a 77% increase in average burned area by 2100 along with increased frequency of extreme wildfires. Additionally, and expected 18% increase in wildfire insurance costs will occur by 2055 [5].

The death toll of the 2018 Camp Fire stood at 88, as of Nov 29 that year [6]. In addition to civilians, firefighters' lives are often on the line when combating wildfires. At least six firefighters lost their lives battling California wildfires in 2018 [7]. As a result, there exists a demand for safer method of conducting search and rescue missions in California wildfires.

1.2 Needs assessment

Citizens of California are often subjected to hazardous environments and in need of rescue if caught in a wildfire. These environments contain uneven terrain, bodies of water, gravel, and sand that are typical to California in addition to flat terrain. Procedurally, it is safer to first put out any fires in the vicinity of the survivors before attempting to find them. Finding any lost survivors separated from their families is also of importance. Lastly, it may be critical to find any food in the vicinity of the survivors, to prevent them from starving.

California wildfires are increasingly putting lives at risk, creating a need for a method of conducting search and rescue operations with the ability to navigate rough terrain, detect and put out a fire, find and deliver food, and locate survivors. As such, the support from the Federal Emergency Management Agency (FEMA), which is currently at a lapse of funding due to government shutdown [8], requires a cost-efficient proof of concept prototype. This proof of concept prototype is the subject of this report.

1.3 Problem Formulation

1.3.1 Problem definition

Design a device to conduct search and rescue operations with the ability to navigate rough terrain, detect and put out a fire, find food and deliver food, and locate survivors.

1.3.2 Desired functions and goals

The device is to be able to locate and put out a fire such as that emanating from a candle, before carrying out other search and rescue operations. Additionally, the device is to be capable of navigating terrain consisting of flat wood, 5 cm steps, water pits, gravel, and sand. Furthermore, the device should be capable of locating a group of survivors, as well as a lost survivor. Survivors are represented using Lego parts and structures. Food, in the form of a metallic ball bearing buried in sand, is also to be detected by the device. Lastly, the device should return to its starting position once all other tasks have been completed.

1.3.3 Objectives

The objectives of the device can be split into physical and non-physical.

Physical:

- Dimensions should be within 0.2 x 0.2 x 0.2 m
- Weigh under 5 kg, such that one person can carry the device
- Able to detect and identify objects such as cardboard walls, Lego structures and people, and a 12 cm candle within a 2.5 m radius
- Able to identify a flame emitted from a 12 cm tall candle within a 1.8 m radius
- Able to extinguish a flame emitted from a 12 cm tall candle within 15 cm of the device
- Able to navigate in an environment with flat wood terrain, sand mounds, gravel mounds, and 5 cm steps down into water pits, with an average speed above 0.3 m/s
- Allows for field swapping of major components in under 5 hours
- Capable of detecting a metal ball bearing buried underneath 5 cm of sand underneath device
- Contain an easy to replace power source (i.e. should be field-swappable)
- Track location within search and rescue site to 5 cm radius of accuracy, such that the device is able to return to its starting position after completing other challenges
- Reliably carry out challenges for a minimum of 10 consecutive missions without intervention

Non-physical:

- Cost under $265 CAD

1.3.4 Constraints

The constraints on the device include:

- Must complete objectives autonomously
- Does not use camera and vision systems
- Does not have flying capabilities
- Stays within boundaries of search and rescue site, marked by cardboard walls

- Does not climb over outer boundary walls
- Must have an average complexity ranking below 7 across all group members

The design complexity ranking is completed by each team member using engineering judgement and previous experience to determine a complexity score between 1 and 10, where 10 is the highest complexity. The scores are then averaged and reported as the design complexity ranking.

1.3.5 Design Selection Criteria

The criteria used for selecting a design include:

- Cost [$]
- Speed [minutes]
- Size [m x m x m]
- Weight [kg]
- Object detection range and accuracy
- Robustness
- Construction complexity
- Reliability

1.4 Key design problems that need to be considered

One of the main design problems that needs to be considered is how the device will navigate through the environment. The environment contains gravel, sand, and water which can cause a device to get stuck or dirty, or malfunction. Additionally, the terrain contains 5 cm steps into the water pits which may be difficult to travel over.

Secondly, the ability to detect and identify several different objects is a key design problem. The device should be capable of detecting cardboard walls, Lego structures and people, a 12 cm candle, and a metal ball bearing buried in sand. Furthermore, the ability to identify and extinguish a flame on a 12 cm candle is a key design problem.

Lastly, another key design problem is navigation. The device should be able to return to its starting position upon completing all other objectives, and thus must be capable of localizing itself within the field and reliability following a safe path. Thus, the main design problems can be summarized as navigating the environment, detecting and identifying objects, and returning to the starting position (self-localization).

2.0 Project Management Work Plan

2.1 Team Resume

The team selected to design, develop, and test this wildfire search and rescue device is comprised of engineers with an expansive set of skills and experience, spanning across mechanical, electrical, software, and project management fields.

Richard (Yangtian) Yan is passionate about electronics hardware and machinery. His past co-op experiences developed his hardware design, bring-up, and testing skills. He is machine shop trained and can operate floor mounted machinery. He is not as experienced in software development.

Celene (Hsuan Ling) Chen has a strong interest in mechanical and technical applications. She has experience in mechanical design and CAD drawing using AutoCAD and SolidWorks in her past co-op experiences and she is also machine shop trained. Celene will need her team members' expertise in software and electrical design.

Briar Smith likes to understand how things work on a fundamental level. His design approach complements this, as he is excellent at saying what is on his mind, and not afraid to ask questions if he doesn't understand something. With most of his co-ops being in embedded systems and his leadership experience on WATonomous, he will be essential in the robot's overall design and success. A subject in which he has less experience is mechanical design.

Ella Rasmussen is an organized and logical thinker. Her software and leadership experiences with VEX robotics and the WATonomous student design team have helped her become a fantastic problem solver. With robotic controls, perception, and project management expertise, she will be an asset to the brain of the robot, design, and success. Areas that she has less experience in are electrical and mechanical design.

Alexander Rathke is a software engineer at heart. His co-op experiences have all been in software engineering roles, including embedded systems. He also thoroughly enjoys the mechanical design he has been exposed to in his undergraduate program. Alex's strengths are developing embedded C++ code, algorithms and data structures, and automation/scripting work. He will rely on team members' input for the electrical design of the device.

2.2 Planning

The work required to develop a search and rescue device has been broken into four main categories to reflect what is required for the project.These four main categories consist of mechanical, electrical, software, and project management. Each category represents a fundamentally different discipline, which can be managed by team members with strengths in the respective category. Figure 1 shows the team's work breakdown structure divided into the four main categories, as well as a further breakdown into the major subsystems or subsections of each category.

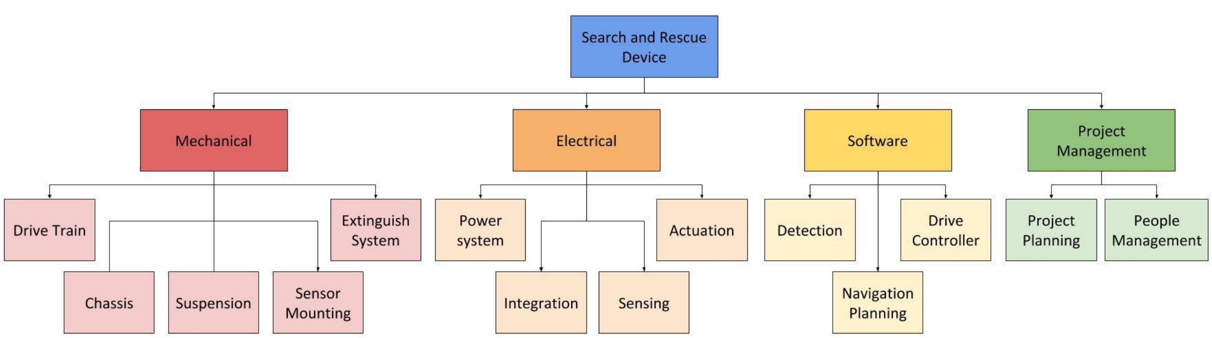

Figure 1: Work Breakdown Structure

The team resume shows that the assigned team members have a diverse set of skills that cover all aspects required for the search and rescue device. To clearly outline responsibilities that play to each members' strengths and interests, a task responsibility breakdown is shown in Table 1. The values shown in Table 1 and their corresponding responsibility levels are as follows:

1. Primary responsibility
2. Support
3. Must be consulted
4. May be consulted
5. Final approval

Ella and Alex are the primary and support software engineers for the device, taking on the software development tasks. Briar and Richard are the primary and support electrical engineers for the device. Celene and Richard are the primary and support mechanical engineers. Briar and Ella are the primary and support project managers. The remaining problem formulation, concept design, presentations, and testing tasks require the support of the entire team.

Table 1: Task Breakdown and Responsibility Assignment

WBS #	TASK TITLE	RICHARD	CELENE	ALEX	BRIAR	ELLA	PROF
1	**Problem Formulation**	**2**	**2**	**1**	**2**	**2**	
1.1	Needs assessment	2	2	1	2	2	
1.2	Research	2	2	1	2	2	
1.3	Problem definition	2	2	1	2	2	
1.3.1	Define problem	2	2	1	2	2	
1.3.2	Define objectives	2	2	1	2	2	
1.3.3	Define constraints	2	2	1	2	2	
1.3.4	Define criteria	2	2	1	2	2	
1.4	Write proposal report	2	2	1	2	2	5
2	**Concept Design**	**2**	**1**	**2**	**2**	**2**	
2.1	Morphological Chart	1	2	2	2	2	
2.1.1	Define subsystems	2	2	1	2	2	
2.1.2	Brainstorm ideas	1	2	2	2	2	
2.2	Design Concept	2	1	2	2	2	
2.2.1	Develop concepts	2	1	2	2	2	
2.2.2	Weigh criteria	1	2	3	3	3	
2.2.3	Decision matrix	2	1	3	3	3	
2.2.4	Select final design	2	1	3	3	3	
2.3	Write proposal report	2	1	3	3	3	5
3	**Project Management**	**3**	**3**	**3**	**1**	**2**	
3.1	Identify team resume	3	3	3	1	2	
3.2	Work breakdown	3	3	3	2	1	
3.2.1	Work breakdown structure	3	3	3	2	1	
3.2.2	Task breakdown	2	2	2	2	1	
3.2.3	Form schedule	3	3	3	2	1	
3.3	Define budget	2	3	3	1	2	
3.4	Identify facilities and equipment	3	3	3	1	2	
3.5	Create risk mitigation plans	3	3	3	1	2	
3.6	Develop group contract	3	3	3	1	2	
3.7	Write proposal report	3	3	3	1	2	5
4	**Detailed Design and Analysis**	**1**	**2**	**2**	**2**	**2**	
4.1	Detailed design specifications	2	1	2	2	2	
4.1.1	Dimensioning	2	1	4	4	4	
4.1.2	Sensor placement	1	2	3	3	2	
4.1.3	CAD/SolidWorks drawings	2	1	3	3	3	5
4.1.4	Part and sensor selection	1	2	2	2	2	
4.2	Preliminary sensor capability test	2	4	4	1	3	
4.3	Preliminary actuator capability test	1	4	4	2	3	
4.4	Calculations	2	2	2	2	2	5
5	**Mechanical Construction**	**2**	**1**	**4**	**4**	**4**	
5.1	Drive train	2	1	4	4	4	
5.1.1	Component fabrication	2	1	4	4	4	
5.1.2	Component fitting/assembly	2	1	4	4	4	
5.1.3	Power integration	1	2	4	4	4	
5.2	Suspension	2	1	4	4	4	
5.2.1	Component fabrication	2	1	4	4	4	
5.2.2	Component fitting/assembly	2	1	4	4	4	
5.2.3	Connect to drive train	2	1	4	4	4	
5.3	Sensor mounting	1	2	4	4	3	

5.3.1	*Fabricate supports*	*1*	*2*	*4*	*4*	*4*	
5.3.2	*Optimize sensor placement*	*2*	*1*	*4*	*4*	*3*	
5.3.3	*Test rigidity and accuracy*	*1*	*2*	*4*	*4*	*4*	
5.4	*Extinguishing system*	*2*	*1*	*4*	*4*	*4*	
5.4.1	*Component fabrication*	*2*	*1*	*4*	*4*	*4*	
5.4.2	*Component fitting/assembly*	*2*	*1*	*4*	*4*	*4*	
5.5	*Chassis*	*2*	*1*	*4*	*4*	*4*	
5.5.1	*Create element protection*	*2*	*1*	*4*	*4*	*4*	
5.5.2	*Validate protection*	*2*	*1*	*4*	*4*	*4*	
6	***Electrical Construction***	***1***	***3***	***3***	***2***	***3***	
6.1	*Power system*	*1*	*4*	*4*	*2*	*4*	
6.1.1	*Supply power to actuators*	*1*	*4*	*4*	*2*	*4*	
6.1.2	*Supply power to sensors*	*1*	*4*	*4*	*2*	*4*	
6.2	*Sensing*	*2*	*2*	*4*	*1*	*3*	
6.2.1	*Wire data signals to MCU*	*2*	*4*	*4*	*1*	*4*	
6.2.2	*Read data signals from MCU*	*2*	*4*	*4*	*1*	*4*	
6.2.3	*Data conversion*	*2*	*4*	*4*	*1*	*3*	
6.2.4	*Calibrate/benchmark sensors*	*1*	*2*	*4*	*2*	*3*	
6.3	*Actuation*	*1*	*4*	*4*	*2*	*3*	
6.3.1	*Motor driver*	*1*	*4*	*4*	*2*	*3*	
6.4	*Integration*	*1*	*4*	*4*	*2*	*4*	
6.4.1	*Integrate with mechanical system*	*1*	*2*	*4*	*2*	*4*	
7	***Software Development***	***4***	***4***	***2***	***4***	***1***	
7.1	*Develop software architecture*	*4*	*4*	*2*	*4*	*1*	
7.2	*Detection*	*3*	*4*	*2*	*3*	*1*	
7.2.1	*Develop detection algorithm*	*3*	*4*	*2*	*3*	*1*	
7.2.2	*Test detection algorithm*	*3*	*4*	*2*	*3*	*1*	
7.2.3	*Iterate*	*4*	*4*	*2*	*4*	*1*	
7.3	*Navigation planning*	*4*	*4*	*1*	*4*	*2*	
7.3.1	*Develop planning algorithm*	*4*	*4*	*1*	*4*	*2*	
7.3.2	*Test planning algorithm*	*4*	*4*	*1*	*4*	*2*	
7.3.3	*Iterate*	*4*	*4*	*1*	*4*	*2*	
7.4	*Drive controller*	*3*	*4*	*2*	*3*	*1*	
7.4.1	*Develop controller(s)*	*3*	*4*	*2*	*3*	*1*	
7.4.2	*Simulate controller(s)*	*3*	*4*	*2*	*3*	*1*	
7.4.3	*Test and tune controller(s) on device*	*2*	*4*	*2*	*4*	*1*	
8	***Whole System Testing***	***1***	***1***	***1***	***1***	***1***	
9	***Presentation***	***2***	***2***	***2***	***1***	***2***	*5*
9.1	*Plan presentation*	*2*	*2*	*2*	*1*	*2*	
9.2	*Practice presentation*	*1*	*1*	*1*	*1*	*1*	
10	***Final Report***	***2***	***2***	***2***	***1***	***2***	*5*

2.4 Schedule

Time management is key in the creation of a successful project. Table 2 below shows a Gantt chart which breaks down all of the task responsibilities and assigns start and end times. Extra time was budgeted for integration and testing of the system. Note week 6 does not have tasks marked for mechanical and electrical construction due to midterm exams happening that week.

Table 2: Task Breakdown Gantt Chart

WBS #	TASK TITLE	OWNER	% DONE	Planning & Design				Construction & Testing						Demo & Report	
				W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12
1	**Problem Formulation**	**Alex**													
1.1	Needs assessment	Alex	100%												
1.2	Research	Alex	100%												
1.3	Problem definition	Alex	100%												
1.3.1	Define problem	Alex	100%												
1.3.2	Define objectives	Alex	100%												
1.3.3	Define constraints	Alex	100%												
1.3.4	Define criteria	Alex	100%												
1.4	Write proposal report	Alex	100%												
2	**Concept Design**	**Celene**													
2.1	Morphological Chart	Richard	100%												
2.1.1	Define subsystems	Alex	100%												
2.1.2	Brainstorm ideas	Richard	100%												
2.2	Design Concept	Celene	100%												
2.2.1	Develop concepts	Celene	100%												
2.2.2	Weigh criteria	Richard	100%												
2.2.3	Decision matrix	Celene	100%												

2.2.4	*Select final design*	*Celene*	*100%*
2.3	*Write proposal report*	*Celene*	*100%*
3	***Project Management***	***Briar***	
3.1	*Identify team resume*	*Briar*	*100%*
3.2	*Work breakdown*	*Ella*	*100%*
3.2.1	*Work breakdown structure*	*Ella*	*100%*
3.2.2	*Task breakdown*	*Ella*	*100%*
3.2.3	*Form schedule*	*Ella*	*100%*
3.3	*Define budget*	*Briar*	*100%*
3.4	*Identify facilities and equipment*	*Briar*	*100%*
3.5	*Create risk mitigation plans*	*Briar*	*100%*
3.6	*Develop group contract*	*Briar*	*100%*
3.7	*Write proposal report*	*Briar*	*100%*
4	***Detailed Design and Analysis***	***Richard***	
4.1	*Detailed design specifications*	*Celene*	*0%*
4.1.1	*Dimensioning*	*Celene*	*0%*
4.1.2	*Sensor placement*	*Richard*	*0%*
4.1.3	*CAD/SolidWorks drawings*	*Celene*	*0%*
4.1.4	*Part and sensor selection*	*Richard*	*0%*
4.2	*Preliminary sensor capability test*	*Briar*	*0%*
4.3	*Preliminary actuator capability test*	*Richard*	*0%*
4.4	*Calculations*	*All*	*0%*
5	***Mechanical Construction***	***Celene***	
5.1	*Drive train*	*Celene*	*0%*
5.1.1	*Component fabrication*	*Celene*	*0%*
5.1.2	*Component fitting/assembly*	*Celene*	*0%*
5.1.3	*Power integration*	*Richard*	*0%*
5.2	*Suspension*	*Celene*	*0%*
5.2.1	*Component fabrication*	*Celene*	*0%*
5.2.2	*Component fitting/assembly*	*Celene*	*0%*
5.2.3	*Connect to drive train*	*Celene*	*0%*
5.3	*Sensor mounting*	*Richard*	*0%*
5.3.1	*Fabricate supports*	*Richard*	*0%*
5.3.2	*Optimize sensor placement*	*Celene*	*0%*
5.3.3	*Test rigidity and accuracy*	*Richard*	*0%*
5.4	*Extinguishing system*	*Celene*	*0%*
5.4.1	*Component fabrication*	*Celene*	*0%*
5.4.2	*Component fitting/assembly*	*Celene*	*0%*
5.5	*Chassis*	*Celene*	*0%*
5.5.1	*Create element protection*	*Celene*	*0%*
5.5.2	*Validate protection*	*Celene*	*0%*
6	***Electrical Construction***	***Richard***	
6.1	*Power system*	*Richard*	*0%*
6.1.1	*Supply power to actuators*	*Richard*	*0%*
6.1.2	*Supply power to sensors*	*Richard*	*0%*
6.2	*Sensing*	*Briar*	*0%*
6.2.1	*Wire data signals to MCU*	*Briar*	*0%*
6.2.2	*Read data signals from MCU*	*Briar*	*0%*
6.2.3	*Data conversion*	*Briar*	*0%*
6.2.4	*Calibrate/benchmark sensors*	*Briar*	*0%*
6.3	*Actuation*	*Richard*	*0%*
6.3.1	*Motor driver*	*Richard*	*0%*
6.4	*Integration*	*Richard*	*0%*
6.4.1	*Integrate with mechanical system*	*Richard*	*0%*
7	***Software Development***	***Ella***	
7.1	*Develop software architecture*	*Ella*	*0%*
7.2	*Detection*	*Ella*	*0%*
7.2.1	*Develop detection algorithm*	*Ella*	*0%*
7.2.2	*Test detection algorithm*	*Ella*	*0%*
7.2.3	*Iterate*	*Ella*	*0%*
7.3	*Navigation planning*	*Alex*	*0%*
7.3.1	*Develop planning algorithm*	*Alex*	*0%*
7.3.2	*Test planning algorithm*	*Alex*	*0%*
7.3.3	*Iterate*	*Alex*	*0%*
7.4	*Drive controller*	*Ella*	*0%*
7.4.1	*Develop controller(s)*	*Ella*	*0%*
7.4.2	*Simulate controller(s)*	*Ella*	*0%*
7.4.3	*Test and tune controller(s) on device*	*Ella*	*0%*
8	***Whole System Testing***	***All***	
9	***Presentation***	***Briar***	
9.1	*Plan presentation*	*Briar*	*0%*
9.2	*Practice presentation*	*All*	*0%*
10	***Final Report***	***Briar***	

2.5 Deliverables

Deliverables for the completion of the device, and their respective due dates, are shown in Table 3 below. These deliverables are taken into account in the Gantt chart scheduling.

Table 3: Project deliverables and due dates

Deliverable	Due Date
Report #1: Proposal and Conceptual Design	January 25
Design Check	February 1
Calculations	February 8
Construction Check	February 28
Presentation	February 28
Game Day (Live Testing)	March 22
Report #2: Final	March 29

2.6 Budget

FEMA is providing a budget of $265 to create the search and rescue device. This includes all mechanical, electrical, and software materials and manufacturing that are required for the entire device to operate. As much assembly and manufacturing as possible is to be done by the group members, such as machining parts, to reduce costs.

Additionally, two rules have been established for any project related purchases. First, any purchases must be approved by all team members. Secondly, all purchases are to be made by Briar Smith, the CFO of Lera Inc.

The allotted budget for the project, broken down by approximate cost per category, is shown in Table 4 below.

Table 4: Search and Rescue Device Allotted Budget Per Category

Expense	Details	Approximate Cost ($)
Mechanical System	Chassis, Suspension, drivetrain, motor mount, battery mount, electronics fixture, sensor mount, motors	50
Machining	3D printing, laser cutting (material)	20
Power System	Batteries, driver ICs	30
Sensors	Distance, light detection, etc.	100
MCU	MCU for computing	20
Consumables	Screws, washers, wires, PCB, project boards, solder, wood, metal, adhesives	25

Miscellaneous	Unexpected failures, extra reinforcements, design change, etc.	20
	Total	265

2.7 Required Facilities and Equipment

The search and rescue device may require custom fabrication of parts if off-the-shelf components are not available. This includes components such as chassis, sensor mounts, battery mounts, motor mounts, drivetrain and suspension parts.

Equipment available for use by at least two of the team members includes the E3 & E5 machine shops, located in the University of Waterloo campus. These machine shops are equipped with tools such as a milling machine, lathe, band saw, grinder, drill, screw driver, and pliers. Furthermore, WATiMake, also located on campus, provides rapid prototyping equipment such as a laser cutter and 3D printer.

2.8 Risk Mitigation Plans and Recovery Tactics

There is a substantial chance that something goes wrong during the design, testing or manufacturing and assembly of the search and rescue device. By following standard design and assembly practices, much of the risk becomes mitigated. For example, best practices for sensor placement, electrical wiring, and the use of high quality, authentic parts will be used in the assembly.

Extra time has been allotted in the Gantt chart, shown in Table 2 above, that allows for a sufficient amount of time to deal with unexpected integration problems and extra testing. As a recovery measure, a part of the budget has been dedicated to miscellaneous costs which account for a design change or hardware failure.

2.9 Group Contract

The following describes an agreement between the team members on how to function as an organized and committed team. This includes methods on how to resolve conflict, make efficient decisions without discouraging creativity, and communicating effectively. Rules have also been made for how to best utilize time during team meetings.

2.9.1 Conflict

In the event of conflict between team members, the following steps are to be taken by the involved members:

1. Prepare a list of expected outcomes from the situation, and how conflicting members can help this outcome be achieved.
2. Members in conflict should express feelings in a calm manner, without interrupting each other, to assure there is no confusion.
3. Work together to determine how the expected outcomes can be achieved.
4. If the conflict cannot be resolved by the affected members, request input from additional group members and come to a solution by taking a vote.

Additionally, if the situation feels tense, members are encouraged to let emotions settle down and revisit the topic once those involved have had time to reflect (expected to be approximately one day).

2.9.2 Communication

Communication is vital to ensuring all members are aware of what needs to be done to reach project completion. Members are encouraged to speak up if they are struggling. However, they should only seek the help of other group members after having researched the problem on their own. The aforementioned rule does not apply if the problem lies outside of the member's area of expertise.

Discord, an online communication platform, will be used as the primary method of communication outside of meetings. To ensure proper communication, each member is encouraged to utilize drawings/sketches and ask for clarification when needed.

To ensure that each group member is aware of the group's and their own responsibilities, daily communication must happen. There are two questions which should be considered daily by each group member. First, what is the group's current and long term objectives? Second, what are the objectives today, this week, and this month? If any uncertainty arises from this, the group member must voice their questions to the rest of the group.

Additionally, in order to make sufficient daily progress, the group member must check to make sure that their own, and the group's work, is aligned with the Gantt chart shown in Table 4. If one falls behind in the Gantt chart, or the group has fallen behind, this also must be communicated to leave enough time for redelegation and planning.

Lastly, any significant progress on the Gantt chart needs to be reflected through a Discord message at the end of each week, or more frequently depending on the significance of the progress made.

2.9.3 Decision making

For any design changes relating to the initially selected high-level concept, the change must be presented to the entire group and decided on by the group as a whole. The final decision on changes to a given system will be made by the system lead, the person with the highest level of responsibility in the given section as indicated in the task responsibility chart shown in Table 1.

Any decisions regarding finances will need to be approved by the entire team with sufficient justification from the requestor.

Furthermore, minor system changes do not need to be approved by the rest of the group. For example, switching to a different type of fastener does not need approval by the rest of the team. A minor system change is essentially anything that doesn't change one of the device's major systems.

2.9.4 Meetings

Meetings will occur weekly on Fridays and Sundays. Meetings may also be scheduled on other days on an as needed basis. It is expected that each member of the group attends these meetings, and arrives prepared. Coming prepared includes knowing the goals of the meetings, and answering the following

- What needs to be accomplished in the meeting as per the Gantt chart?
- What should the outcome of the meeting be, according to the Gantt chart?

The above points apply even if the meeting is about something that is not aligned with the Gantt chart.

Additionally, members should approach meetings with a focused mindset, understanding that the meeting is to accomplish a specific task and is using everyone's time. This means that behavior such as having an off topic conversation about items not related to the project or not within the goals of the meeting are to be minimized. Additionally, team members are encouraged to not show up late to meetings. If a person has shown up late 4 times they are required to buy the rest of the team bubble teas from The Alley bubble tea shop.

Group members are equally responsible for calling meetings as needed, and each person is responsible for calling meetings with the appropriate people as seen fit. However, it should be announced to the group that a sub-group of members are meeting about something specific, for example, motor characterization.

4.0 Conceptual Design

4.1 Morphological chart

To achieve the main objectives of the search and rescue prototype, the device includes a number of sub-functions that can each be achieved by various possible approaches. The sub-functions are listed and described below.

Drivetrain: The vehicle is required to navigate through various terrains during the mission. The drivetrain design should have off-road capabilities and speed to accommodate for this objective.

Fire Extinguishing: The mission requires the vehicle to detect and extinguish a fire represented by a candle.

Fire Detection: The fire extinguishing equipment can often have very limited use, require a high accuracy, and can cause collateral damage if fire is mis-identified, thus detection is an important component of fire elimination. Also, in a search and rescue mission, detecting the fire accurately and quickly can ensure the safety of the entire operation.

Food Detection: In natural disaster, useful supplies can be buried. The device needs to be equipped with detection devices to locate and identify the buried food item, represented by a metal ball bearing.

Object Detection: There are numerous other objects in the field to be detected and identified, such as the sandbox border, and structures containing survivors.

Navigation: The device needs to plan its path to the target object, avoid potential hazards, and return to the starting point at the end of the mission.

Water Navigation: The water inside the field introduces unique challenges to the device. The drop off into the water area can cause the device to become stuck. If the device enters the water pit, it needs to climb up a 5 cm step to exit the water area. Due to the different physical properties of the water compared to other objects, it requires separate implementation for navigation around and in water.

For each sub function, a number of alternative implementation concepts are generated and presented in the morphological chart in Table 5 below.

Table 5: Morphological box presenting concepts for different sub-functions

Sub-functions	**Alternative Concepts**				
Number of device units	Single	Multi			
Drive train	Wheels	Treads	Hamster ball	Screwdriver boat	Legs
Fire Extinguishing	Targeted spray	Non-targeted spray	Fire suffocation		
Fire Detection	Heat	CO_2	Light / IR	None (To be used in combination with non-targeted spray)	
Food Detection	Magnetic field detection	Pressure-based detection	Sand sifting		
Object Detection	Distance sensors	Touch Sensor	Colour Sensor		
Navigation	Orientation sensors	Distance sensors			
Water Navigation	Amphibious	Detect water and avoid			

4.2 Design Concepts

This section contains five conceptual designs generated from the morphological box, a brief description and the proof of concept for each concept design are also provided.

4.2.1 Design Concept 1: Tank

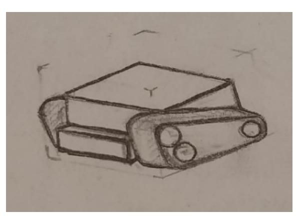

Figure 2: Tank Concept Design

This concept consists of a conventional box shaped chassis mounted to a wheel or tracked suspension. The chassis protects the sensors and internal components from the elements and provide structural support. The suspension provides enough ground clearance and mobility.

Due to the design's stable build and larger size, it is capable of using fire suffocation which is a reusable method for fire extinguishing. The design uses light/IR for fire detection and magnetic field detection for food detection. However, the treads in the design makes the vehicle harder to complete turns, which decreases the accuracy for steering.

Tanks and tractors are a proven design concept used often for multi-terrain transportation.

4.2.2 Design Concept 2: Hamster Ball

Figure 3: Hamster ball Concept Design

The design uses the concept of moving over terrain with an internal power and traction system. The spherical structure of the design enables the vehicle to freely rotate in any direction and all positions are stable. Its propulsion system is placed inside the ball and can be sealed to provide a waterproof environment for the interior parts important for semi-submerged applications. The hamster ball concept would need targeted spray at its two side as the fire extinguishing method due to its spherical shape and method of transportation. All the other components for food detection and distance sensors will be sealed within the sphere and protected from the water, which makes the vehicle available to travel in water.

The design's technical challenges are its limited off-road capability and challenging controllability. The possibility of rotation in all directions makes the control of the ball challenging. Ball oscillation during the movement is difficult to handle, while the control system requires powerful actuators to compensate the oscillations.

Ball-shaped autonomous moving vehicles have a long history, and recent studies have described a variety of applications in different environments, including marine, indoors, outdoors, zero-gravity and planetary exploration [9].

4.2.3 Design Concept 3: Spider

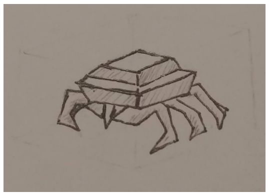

Figure 4: Spider Concept Design

This design incorporates the concept of insect locomotion as it has a few legs that mimics that of an insect. The multi-legged robot moves by the alternating motion of each leg where the contact between the robot and ground is a series of discrete points. This design also enables easy and stable movements through uneven surfaces, steps and areas that would be difficult for a wheeled vehicle to reach [10]. Touch sensors can be attached to each of the robot limbs and be used to detect objects and water. With its multiple limbs and touch sensors, the robot can use sand sifting with its multiple legs to locate the food that is buried in the sand pit and its front legs can be used to touch and detect for water in order for the robot to avoid the route. This robot design would be capable of both the targeted spray and the fire suffocation method as its fire extinguisher system. The major challenge of this design is the slow speed of the locomotion and control of a compliant legged robot.

Hexapod robots are common and proven design concept based on insect locomotion [10].

4.2.4 Design Concept 4: Spider Wheel

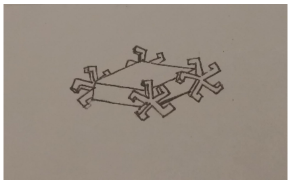

Figure 5: Spider Wheel Concept Design

Concept 4 has wheels that have extended hooks or legs which enables the vehicle to climb stairs and other obstacles. The Spider Wheel design uses a targeted spray to complete the fire extinguishing task and light/IR for fire detection. For food detection, this robot is able to use pressure-based detection from its legs and uses touch sensor for object detection. Due to the angles and position of the extended hooks, the speed, steering and stability of the vehicle are to be examined in detail if this design is implemented. The shaped wheels will help the robot to climb steps and walls which can potentially make it amphibious given enough water protection of electrical components. For navigation and other subfunctions, the Spider wheel has similar disadvantages as the tank concept, in addition to a lower level of sensor detection stability due to the method of motion.

The design concept has been tested and proven to work by its developers, Prof. Meredith Thring and Brian Shayer at Queen Mary College, London University for wheelchair applications [11].

4.2.5 Design Concept 5: Multiple Robots

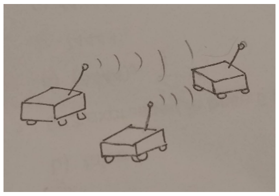

Figure 6: Multiple Robots Concept Design

This concept has multiple vehicles executes search and rescue operation in different areas of the board simultaneously. The units can equip the same abilities and divide the work area, or have different units specialized in their role (e.g. finding food, survivor searching). To prevent repetitive effort and increase efficiency, communication is established between the units to operate collectively. The drive train of this design concept uses wheels which is faster, cheaper, and more reliable and uses non-targeted spray for fire extinguisher due to the large area that the robots are able to cover in a larger scale. The robots are designed to detect and avoid water due to the individuals robots small sizes which makes it harder for them to climb out of the water. Each of the robots would have to contain orientation sensors and distance sensors for navigation purposes.

Kilobots, developed by Wyss, are designed and proven to work as artificial swarms of robots collaboratively working together towards a common goal [12].

4.3 Evaluation of Design Concepts

In order to choose the best of the proposed design concepts, criteria must be compared against each other. This comparison is shown in Table 6 by assigning weightings of 0 (less important), ½ (same level of importance, or 1 (more important) in order to indicate the relative importance of each criterion to one another.

Table 6: Ranked Criteria

	Size	Weight	Accuracy	Robustness	Speed	Cost	Reliability	Complexity of Design	Total / Rank
Size	-	1/2	0	0	0	0	0	1/2	1/6
Weight	1/2	-	0	0	0	0	0	1/2	1/6
Accuracy	1	1	-	0	1/2	1	0	1	4.5/3
Robustness	1	1	1	-	1	1	1/2	1	6.5/1
Speed	1	1	1/2	0	-	1	0	1	4.5/3
Cost	0	0	0	0	0	-	0	1/2	0.5/8
Reliability	1	1	1	1/2	1	1	-	1	6.5/1
Complexity of Design	1/2	1/2	0	0	0	1/2	0	-	1.5/5

Reliability, the vehicle's ability to consistently perform up to its designed capabilities, and robustness, how well the vehicle operates under any given complex terrain, are the top ranked criteria. While having consistency, the speed the vehicle operates and its accuracy when detecting mission critical objects are the next important items. The complexity of design is the next important item. A low complexity provides ease of prototyping, bring up, debugging, as well as reliable operation. The size and weight are the lowest ranked criteria, since the size of the vehicle has no hard constraint, and the weight limit (can be lifted by a single person) is generous for the size being designed for.

Based on these rankings, each of the criterion are given a weighting as shown in Table 7 below. The scale for criteria weightings is from 0 to 10, where 0 to 3 is optional, 3 to 7 is important, and 7 to 10 is critical to the design.

Table 7: Design criteria and their respective weightings

Ranked criteria item	Weighting
Reliability	10
Robustness	10
Speed	7
Accuracy	7
Complexity of Design	4
Cost	2
Size	2
Weight	2

Minimizing cost, size, and weight are weighed as optional criteria because the project still has a high chance of succeeding even if it exceeds FEMA's objective cost of $265, objective maximum size of 0.2x0.2x0.2 m, and objective weight of 5 kg. The speed, accuracy, and complexity of design are all assigned important weights since they affect the performance of the device by allowing for more frequent and faster completion of rescue missions and a shorter device construction time. Reliability and robustness are critical weightings because they determine if the life-saving missions will be completed at all.

4.4 Design Elimination

After evaluating the concepts, the multi-robot concept is eliminated as it requires sophisticated wireless communication between all units, and extremely complex navigation for coordinating numerous autonomous devices to cover the operation area. After a group discussion, the team determined that the complexity ranking of this design is 9 since implementing a design with such complexity is beyond the group's capabilities in the given time and budget. Since this complexity ranking is higher than the maximum ranking of 7 defined in the constraints, the design must be eliminated from further analysis.

4.5 Design Selection

In order to select a design to proceed with into the detailed design phase, the design matrix shown in Table 8 below, ranks each design against the design criteria. Each design's criteria ratings are multiplied by the weighting of the corresponding criterion and totalled together to generate the overall score for the design. The design with the highest score is selected as the final design.

Table 8: Decision Matrix

	Size		**Weight**		**Accuracy**		**Robustness**		**Speed**		**Cost**		**Reliability**		**Complexity of Design**		**Total / Rank**	
Designs \ WF	2		2		7		10		7		2		10		4			
Tank	4	8	5	10	8	56	8	80	7	49	8	16	8	80	10	40	339	1
Hamster Ball	10	20	6	12	2	14	5	50	8	56	7	14	6	60	4	16	242	3
Spider	2	4	5	10	6	42	6	60	4	28	4	8	4	40	3	12	204	4
Spider wheel	4	8	5	10	4	28	6	60	4	28	8	16	7	70	7	28	248	2

Designs are assigned their respective scores for each criteria based on the following comparisons.

Size

A device which occupies a smaller volume obtains a higher score, as it is more likely to pass size restrictions and likely be able to navigate the course easier. The spherical hamster ball is able to occupy a smaller potential volume than other designs, thus is assigned the highest rating for size. The tank and spider wheel designs received the same lower score because they both rely on suspension installed on the sides of the device, taking up additional space. Furthermore, a wide track is required for traction and stability. The spider design received the lowest score due to the large span of the legs.

Weight

A lightweight design receives a high score, as it will better be able to traverse terrain such as sand and climb over inclines. Additionally, lighter designs will require less power draw to drive. Due to the number of tasks the devices must achieve that require specialized equipment, none of the concepts excel in this area. The hamster ball design scores the highest due to its integrated drivetrain. All other designs consist of a chassis and various types of suspensions attached to the chassis, achieving similar low scores for weight.

Accuracy

Accuracy is a measure of how well the device can obtain stable sensor readings of interest. The more reliably the device can obtain relevant readings, the higher the accuracy. The tank design obtains the highest score due to high platform stability, the suspension also helps to gather smooth data when device is moving. The spider concept is stable standing still but does not move steadily due to the method of movement. The spider wheel concept is less stable due to the spoked wheels causing a bumpy drive pattern. The hamster ball design scores the lowest due to the relatively unstable chassis.

Speed

For this criterion, the fastest design has the highest score. The hamster ball scores the highest due to its highly integrated drivetrain and the largest track diameter, enabling it to cross various terrain with ease. The tank design is also high speed, due to the high versatility of the traditional suspension. The legged spider and spider wheel designs are slow because their drivetrains provoke rocking motion of the chassis when moving, although they can be more suitable for step climbing and certain rough terrain traversing.

Reliability

A more reliable design results in a higher score. The tank design receives a high reliability score due to the simplicity and maturity of the suspension structure. The smooth action of the device can also easily prevent internal components from vibration. The spider wheel is a derivation of the tank design with slightly lower reliability due to the weaker legged wheels comparing to circular wheel or track designs. The hamster ball has medium reliability. Its integrated structure can provide protection to the internals, but the lack of suspension and low maintainability and accessibility to the internals can hinder its reliability. The spider design is the most unreliable design due to the complexity of the legs.

Robustness

Higher levels of robustness (better ability to navigate through rough terrain) results in a higher score. The tank design performs most consistently throughout all terrains and gains a high score. The hamster ball is extremely fast on flat ground, but can suffer climbing up steps, thereby receiving the lowest score. The spider and spider wheel designs both bias toward step climbing and complex terrain traversing, sacrificing speed for all-terrain possibility. Thus they receive a score slightly higher than that of the hamster wheel.

Complexity of Design

The complexity of the design can take up a large portion of the team's time to draw and build the project, preventing the team from being able to work on other important milestones. A design concept can easily become overly complicated without significant added benefit to the performance. Hence, a more complex design has a lower score. The tank design is the least complex design. The spider wheel concept is based on the tank design with slight modification from the suspension, with a relatively low complexity as well. The hamster ball design requires unconventional design and internal layouts, therefore it scores low. The spider concept is the most complicated in term of drivetrain, scoring the lowest.

All criteria items of each concept are quantified and displayed in the decision matrix above, shown in Table 8. The tank design has obtained the highest score, thus it has been chosen as the final design.

5.0 Conclusions and Recommendations

FEMA's need of a method to conduct search and rescue operations to provide first response for wildfires and times of disaster can be resolved with an unmanned autonomous robot. With limited funding, designing and prototyping of a cost-efficient vehicle demonstrates the plausibility of helping FEMA and citizens of California to increase effectiveness and reduce risk involved in search and rescue operations.

The device must be able to locate and put out a fire emanating from a candle, before carrying out other search and rescue operations, be capable of navigating terrain consisting of flat wood, 5 cm steps, water pits, gravel, and sand and be able to locate food in the form of a metallic ball bearing buried in sand, a group of survivors, as well as a lost survivor and return to the starting position once all tasks have been completed.

A team of 5 talented Lera Inc. engineers is assembled to take on this task. The team members possess various experiences and interests, ranging from software development, mechanical CAD, and hardware bring-up, to managing a university autonomous vehicle team. The project is divided into 4 main categories: Mechanical, Electrical, Software, and Project Management. Each category contains sub-category to help assigning specific tasks to specific members.

Provided with the objectives of firefighting, search and rescue, and a budget limit of $265, several design concepts are proposed, from the off-road tank, to a spherical hamster ball design, and were evaluated against criteria items. The multi-robot design, although it has superb potential efficiency, was deemed unrealistic to develop given the limited resources and timeframe; The hamster ball design, although highly integrated and quick moving, does not provide enough stability for accurate sensor readings. A few specialized suspension configurations, such as spider leg and spider wheel, were evaluated as well, but their all-terrain speed and agility are no match for the mature conventional tank design. The tank concept is the chosen design to continue its development, as it achieved the overall highest score from the decision matrix, and will be further developed in the proceeding stages of the project.

It is recommended that the team members communicate with each other more proactively throughout their tasks to reduce the time consumed for synchronization and adjustments toward the end of a project stage.

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