July 10, 2022

Dr. Craig Scratchley
School of Engineering Science
Simon Fraser University
British Columbia, V5A 1S6

NATURE COOLERS

RE: ENSC 405W/440 Design Specification for Ember Trailer

Dear Dr. Scratchley,

The following document outlines the design specifications for *Ember Trailer*. The goal of *Ember Trailer* is to assist wildfire responders while they sweep the area for any remaining hotspots that could potentially reignite the suppressed or contained wildfire. Our hope is to make it easier for wildfire responders to find said hotpots and to reduce the time required to thoroughly search the surrounding areas after a wildfire has occurred.

This design specification document will detail the functionality and designs in the prototyping of *Ember Trailer*. The design specifications are tailored to meet all the requirements outlined in the previous requirements specifications document.

Our team at Nature Coolers comprises 6 diligent and experiences senior engineering students: Rachel Djauhari, Kevin Lo, Jake Mix, Richesh Patel, Alfred Rodillo, and Xixuan Song. The combination of Computer and Systems Engineering will aid in realizing this project.

We would like to extend our gratitude for taking the time to read and review this design specifications document. If you have any further questions, please feel free to contact me at jmix@sfu.ca.

Sincerely,

Jake Mix
Chief Executive Officer
Nature Coolers

NATURE COOLERS

Design Specification:
Company 3 — Nature Coolers
Ember Trailer

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Submitted To:
Dr. Craig Scratchley, ENSC 405W
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1.0

Abstract

This document summarizes the design specifications for Ember Trailer, the system to detect and prevent wildfires from re-igniting. Presented are design specifications for each phase of the product development (alpha, beta, production) as well as some design features that would hopefully be implemented in future refinements of the product. For each specification mentioned, a justification is provided to explain the basis of why that design choice was made.

Ember Trailer contains 3 main subsystems: detection of the embers/hotspots, suppression of the embers/hotspots, and a communication system to communicate information and data to HQ and responders. Most of the hardware, mechanical, and electrical components will be contained in the module that will attach to a UGV while the software portion focuses on communication and an interface for responders to use to manually control the module.

The design specifications will be categorized into electrical, mechanical, hardware, and software specifications. Also, included as an appendix will be an overview of the user interface design which highlights different analyses, testing methods, engineering standards, and a mock-up design for the software interface. The final details for the proof-of-concept prototype will be completed and delivered by August 2022.

Acknowledgements

The team at Nature Coolers would like to acknowledge the time and efforts of Dr. Craig Scratchley, Mohammad Soltanshah, and Nahid Qaderi. The team appreciates the valuable feedback the professor and teaching assistants have given, especially during company progress review meetings.

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Version History

Table 1. Design Specification Document's Version History

Version Number	Implemented By	Revision Date	Approved By	Approval Date	Reason
1.0	Rachel, Jake, Richesh, Kevin, Alfred, Xixuan	06/22/22			Initial Design Specification Draft

Glossary

The following table includes a list of terms mentioned throughout the paper.

Table 2. Glossary Definitions

Term	**Definition**
UGV	Unmanned Ground Vehicle
Dry-Mopping/ Mopping-Up	Process of extinguishing residual fires and/or embers to ensure the fire does not spread outside of a containment zone
PC	Personal Computer
MCU	Microcontroller Unit
Hotspots	Areas of possible reignition
POC	Proof-of-concept
RPM	Revolutions per minute
PPM	Parts per million

1. Introduction

The Ember Trailer module is a system designed to assist wildfire responders in dealing with wildfires worldwide. The module uses infrared technology, as well as other additional sensors, to detect left-over hotspots that have the potential of reigniting a wildfire. After the initial detection, the system will either alert responders if the hotspot is too large or deep or suppress the heat itself.

Currently, wildfire responders undertake a grueling process called “dry-mopping” which involves scavenging the surrounding area of a contained or suppressed wildfire to find and extinguish hotspots that could cause a second wildfire [1]. This time-consuming process will be ameliorated by Ember Trailer. Responders can leave the detection of hotspots to a UGV, an unmanned ground vehicle, that has the Ember Trailer module attached to it. The suppression of smaller hotspots will also be taken care of by the suppression subsystem.

Ember Trailer consists of 3 main subsystems: a sensor system (for the initial detection), a transceiver module (to communicate with HQ and responders), and a suppression system (to cool down detected hotspots). Each of these core systems require design specifications outlining the technical details of their functionality to meet the requirements listed in the requirements specifications document [2].

1.1 Scope

This document outlines the design specifications chosen and used for the development of Ember Trailer. The specifications will be divided into general, electrical, mechanical, hardware, and software. For each specification, there will be an explanation detailing why that design decision was made.

1.2 Intended Audience

The intended audience of this document is the team of engineers in charge of the implementation of the design of Ember Trailer. This document also serves as a guideline for the professors and teaching assistants involved in overseeing the planning and development of this product.

1.3 System Overview

As mentioned previously, Ember Trailer consists of 3 main subsystems working together. Figure 1 displays how each subsystem interacts with the other components of Ember Trailer.

Outlined in red is the detection subsystem containing all the sensors that would identify any embers/hotspots to be extinguished. The information obtained from the thermal camera and the CO^2 sensor will help to recognize the surface embers/hotspots that pose a threat and need to be cooled down. The drill linear actuator and the drill motors will help to find subterranean embers with the potential of reigniting the suppressed fire. With the temperature probe, which is controlled by the analog pins on the Arduino, attached to the drill system, data can be gathered to determine the temperature rating of the ground. Additionally, the GPS will indicate to responders and to HQ the location of the embers that have been found and need human assistance with putting it out. Finally, the ambient temperature sensor ensures that the internal temperature of the system does not get too high since the Ember Trailer module will be operating under warmer conditions than normal.

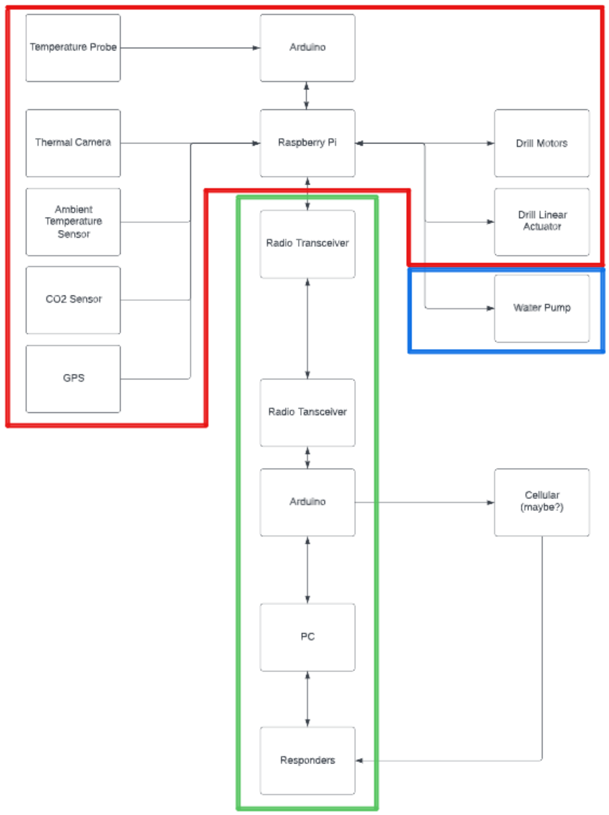

Fig. 1. Design and interaction of the Ember Trailer System

The next subsystem is the suppression system which is outlined in blue. The single controllable component of this system is the water pump. When a hotspot is detected, the suppression subsystem will be alerted, and a responder can begin the process to pump out water to cool it.

Both the detection and suppression components will be mainly controlled by the Raspberry Pi which will also be controlling part of the last subsystem, the communication subsystem, outlined in green. The Raspberry Pi will control a radio transceiver which will mostly work to send data to HQ. HQ will then receive the messages via an Arduino microcontroller controlling another radio transceiver. This Arduino will be connected to a PC that HQ/responders will have access to.

An additional component that is currently out of scope but is part of the design and will hopefully be implemented in the future is the cellular connection between the Arduino directly to responders who are actively at the scene of the fire. This will help to create a faster response and easier access to information that Ember Trailer gathers and analyzes.

1.4 Document Outline

The following main categories will be covered in this document:

1. General Design Specifications
2. Electrical Design Specifications
3. Mechanical Design Specifications
4. Hardware Design Specifications
5. Software Design Specifications

At the end of this document, there will also be a User Interface Design Appendix which summarizes the design requirements for the appearance and usability of Ember Trailer's interface. Additionally, there will be a second appendix detailing the supporting test plan to verify the design specifications mentioned in the document.

1.5 Design Specification Classification

The requirements listed in each requirements section will be classified as follows:

D{Section}.{Subsection}.{Specification Number} {Development Phase}

If the specifications are not listed under a specific subsection, then '0' will be used to indicate that no subsection applies.

For the development phase, the different phases are listed below with the encoding that will be used.

Table 3. Development Phase Encoding

Encoding	**Development Phase**
A	Alpha Phase
B	Beta Phase

The Alpha Phase outlines specifications that must be completed by the end of ENSC 405W which ends in August 2022. This portion will contain our proof-of-concept prototype. The Beta Phase outlines specifications that must be met by the end of ENSC 440 which ends in December 2022. This portion will contain the refined prototype ideally ready to go into production.

2. General Design Specifications

The following table states the design choices made for the system. There will be 2 different types of MCUs operating all 3 subsystems. The Raspberry Pi provides higher quality for the thermal camera, but it does not contain analog pins, therefore the Arduino will be controlling the temperature probe. The suppression system will be closely connected with the drill system at the front of the UGV to minimize the payload and cost of the system. More details regarding each component are given in the following sections.

Table 4. General Design Specifications

Design Specification ID	**Requirement ID Referenced**	**Description**
D2.0.1 A	R3.0.1 B	The system has 3 subsystems: detection, suppression, and communication.
D2.0.2 A	R3.0.2 B	The detection system consists of 2 MCUs and their connected components: 1. Raspberry Pi - Thermal camera - Ambient temperature sensor - CO2 sensor - GPS

		- Drill motors - Drill linear actuator 2. Arduino - Temperature probe
D2.0.3 A	R3.0.3 B	The suppression subsystem contains the water pump.
D2.0.4 A	R3.0.4 B	The communication subsystem will have the radio transceivers. One will be connected to the Raspberry Pi and the other to an Arduino.
D2.0.5 B	R3.0.5 B and R3.0.6 B	The module will be mounted with screws onto a UGV's back and front-side and will be sized accordingly so as not to impede the UGV's operation. The reference for a UGV is Boston Dynamic's Spot.
D2.0.6 A	R3.0.7 A and R3.0.8 A	The module will primarily use the thermal camera and the CO^2 sensor to detect hotspots. Then, if needed, if will use the drill system and the temperature probe to check the depth of the hotspot.
D2.0.7 B	R3.0.9 B	The module will use the radio transceivers to send relevant information to the PC at HQ when it has detected hotspots.
D2.0.8 B	R3.0.10 B	The module will carry a water/suppressant tank that the water pump will use to cool down smaller embers and hotspots.

3. Electrical Design Specifications

3.1 Power Supply

The power supply needs to power all components of the Ember Trailer. Various components will need different voltage ratings; therefore, a buck converter will be needed for those components. The motors for the entire module need a voltage of 12V. Both the Arduino and Raspberry Pi need a voltage rating of about 5V. So, a buck converter for a 12V to 5V drop will be needed.

For the current, a Raspberry Pi is rated for 3A at 5V. The maximum current draw for an Arduino is 2A. The Arduino should be able to power all sensors and camera with that current, since those components do not need an external power supply to use them, and they do not require too much power.

For the stepper motor controller to power the stepper motor (see section 5.1 and 5.2) it will draw at least 3A. For the DC motor controller to power the water pump and the drill (see section 5.1 and 4.1), it can draw 2A per channel at maximum, and two channels are needed to 4A in total.

The total power would be the sum of the power dissipated by each component. For one individual component:

$$Power = Current \times Voltage \tag{1}$$

Using the above equation for all electronic components and summing them up gives a total power consumption of 113W. We will round up to 120W for any discrepancies.

Table 5. Power Supply Specifications[1]

Design Specification ID	Requirement ID Referenced	Description
D3.1.1 A	R4.1.1 A	The power supply shall supply 12V.
D3.1.2 A	R4.1.1 A R4.1.2 A	The power circuit shall provide the correct voltages for various electronic components with the use of buck converters.
D3.1.3 B	R4.1.4 B* R4.1.5 B*	The power supply shall be rechargeable through a 120V wall outlet.
D3.1.4 B	R4.1.2 A R4.1.6 B	The power supply will need to output at least 120W continuously at max load.
D3.1.5 B	R4.1.3 B	The power supply shall have a protective shell for heat and external damage.

3.2 Wiring

To prevent communication breakdown between sensors, actuators, and the MCUs, insulated silicon jumper wires will be used for connections. They will be secured behind a plastic shield to prevent physical damage from the environment. These wires will be heat resistant to withstand the high ambient temperatures along with any heat produced by the UGV or Ember Trailer.

Table 6. Wiring Specifications

Design Specification ID	Requirement ID Referenced	Description
D3.2.1 A	R4.2.1 A R4.2.3 B	Wires will be tightly fasted to each sensor, actuator, and MCU. Zip ties and plastic casing will ensure UGV movement does not break or unplug connections.
D3.2.2 A	R4.2.2 B	Silicon, heat resistant wires will be used.

4. Mechanical Requirements

The general mechanical design requirements involve the entire system. These requirements are based on the reference UGV (see section 2). Also, there will need to be a heat resistive protective material for the entire module. Aramid fibres will be used because they are a common material in

[1] * indicates that the requirement phase has been modified as suggested from the feedback received for the Requirements Specifications Document

firefighting equipment [3] and there has already been a drone that has used aramid fibers to become fireproof [4].

Table 7. General Mechanical Specifications

Design Specification ID	Requirement ID Referenced	Description
D4.0.1 B	R5.0.1 B	The Ember Trailer shall weigh no more than 30lbs.
D4.0.2 B	R5.0.2 B R5.0.3 B R5.0.5 B R5.0.6 B	The Ember Trailer shall have a protection shell to protect itself from heat and external damage.
D4.0.3 B	R5.0.2 B R5.0.3 B R5.0.5 B R5.0.6 B	The Ember Trailer's protective shell shall have aramid fibers to protect itself from heat.
D4.0.4 A	R5.0.1 B	The Ember Trailer shall be no more than 1100mm long and 500mm wide.
D4.0.5 B	R5.0.4 B	The Ember Trailer shall be mounted on top of the UGV using the payload brackets of the UGV.

4.1 Suppression Module

The suppression system will consist of multiple, smaller components. The water, or suppressant, tank will be mounted onto the back of the UGV via screws. This will be a simple and accessible tank that will hold the suppressing liquid for the system. Boston Dynamics' robotic dog "Spot" as a baseline for the UGV, its maximum payload is around 14kg or 30.9lbs [5]. The conversion of kg to litres, for water at a density of 1kg/L and at a temperature of 4°C, is a 1:1 ratio. Knowing this module will be near wildfires and exposed to higher ambient temperatures, it must be assumed the suppressant will also heat up. The tank will be constructed from plastic to mitigate the temperature increase of the liquid inside. At a maximum capacity of 14kg, a good suppressant payload will be approximately 8kg or 8L, which leaves enough room for the sensing and drilling equipment.

The tank will hold water and a small, submersible water pump that will have its power supply controlled by our MCU. To be able to effectively output water at an acceptable flow rate, a 12V 800L/h water pump with a 1/2" male thread was chosen. The pump is the only component that may be affected by higher temperatures. The water stored in the tank will increase or decrease to the ambient temperature, assumer to be around 38°C [6]. The selected water pump operates up to 60°C, thus if the pump's operation increased the water temperature by maximum 10°C, if could still operate under these conditions. Given the equation for volumetric flow rate and its rearranged form to solve for fluid velocity,

$$R = vA \tag{3}$$

$$v = \frac{R}{A} \tag{4}$$

where v is the liquid's flow velocity, A the cross sectional area of flow, and R the flow rate, the velocity of the liquid can be found from (4),

$$v = \frac{R}{A} = \frac{R}{\pi(\frac{d}{2})^2} = \frac{800L/h}{\pi(0.25in)^2} = \frac{0.000222m^3/s}{\pi(0.00635m)^2} = 1.754m/s \quad (5)$$

The nozzle will be positioned on the underside of the UGV for the easiest access to the ground which it must extinguish. It will be held close to the drone's body so that it does not impede movement by contacting with the ground or any obstacles the UGV may be stepping over.

Table 8. Suppression Module Specifications

Design Specification ID	**Requirement ID Referenced**	**Description**
D4.1.1 A	R5.1.1 B	The suppression nozzle will be placed on the underside of the UGV for better access to embers.
D4.1.2 A	R5.1.5 A	The suppression hose will be 30 inches in length.
D4.1.3 A	R5.1.3 B	The water tank will hold up to 8kg of water with the pump submerged inside.
D4.1.4 A	R5.1.2 B	The water tank will be secured to the back of the UGV via screws and clamps.
D4.1.5 A	R5.1.4 A	The suppression hose will be clamped to the module using U-brackets.

5. Hardware Requirements

5.1 Drill Module

The drill module consists of 2 parts: the drill and the linear actuator. The drill is a DC motor, and it is attached to an auger drill bit via a drill chuck. The DC motor will be rated for 12V. An auger drill bit is used because it is a common tool for boring holes into soil [7]. A drill bit length of around 12 inches is needed for the Ember Trailer. The linear actuator holds the drill and controls the vertical motion of the drill. The actuator is a stepper motor linear actuator because it is precise and is smaller in length relative to its stroke length compared to the other options. It also provides a simple mounting method for the drill. A chosen linear actuator has a NEMA23 stepper motor which requires about 3A and 12V.

Torque is important when reaching dense soil and the higher the RPM the lower the torque [7]. An approximation of the rotary speed of the motor can be made based on other materials and drill diameters. The tables shown in reference [8] indicate that with "harder" materials, a lower RPM is preferred. A larger big diameter indicates a lower RPM. A 2cm diameter for the bit is needed to fit the thermocouple into the hole (see section 5.4). In woodworking, for auger drilling, the recommended speed is 600-700 RPM [9]. Using the recommended speed for woodworking as a reference, a speed of 700 RPM or lower can be chosen.

Using various online suppliers (example drill bit in reference [10]), auger drill bits seem to have a mass of about 500g when the diameter is 2cm and length is around 12 inches.

The torque required to rotate an auger drill bit of the above specifications, 700 RPM, and 1 second ramp time is as follows:

$$\tau = I\alpha \tag{6}$$

τ = torque
I = moment of inertia

$$I = \frac{1}{2}mr^2 = \frac{1}{2}(0.5)(0.01)^2 = 0.000025 \tag{7}$$

α = angular acceleration

$$\alpha = \frac{\Delta\omega}{\Delta t} = \frac{700\ RPM}{1s} = \frac{70\pi/3}{1} = \frac{70\pi}{3} \tag{8}$$

Inserting angular acceleration and moment of inertia calculations into equation 6:

$$\tau = I\alpha = 0.000025\left(\frac{70\pi}{3}\right) = 0.00183\ N \bullet m \tag{9}$$

Table 9. Drill Module Specifications

Design Specification ID	**Requirement ID Referenced**	**Description**
D5.1.1 A	R6.1.1 A	The drill module shall have vertical motion for digging into the ground.
D5.1.2 A	R6.1.1 A R6.1.3 A R6.1.4 A R6.1.5 B R6.1.6 A	The drill module's vertical motion shall be controlled by a rail stepper motor linear actuator.
D5.1.3 A	R6.1.3 A R6.1.4 A R6.1.5 B R6.1.6 A	The drill module shall be placed in front of the UGV for simpler operation.
D5.1.4 B	R6.1.1 A	The drill module will drill up to 20cm in depth
D5.1.5 A	R6.1.1 A	The drill shall use an auger drill bit.
D5.1.6 A	R6.1.1 A	A DC motor with a drill chuck attachment shall act as the drill.
D5.1.7 A	R6.1.1 A	The DC motor shall have a rotary speed of 700 RPM at maximum.
D5.1.8 A	R6.1.1 A	The DC motor shall be mounted to the linear actuator rails.
D5.1.9 A	R6.1.1 A	The DC motor shall have a torque of at least 0.00183 N•m.

D5.1.10 B	R6.1.2 B	The drill module shall have a protective shell for heat and external damage.

5.2 Communication Module

The communication module consists of the Raspberry Pi and an Arduino. A Raspberry Pi contributes very little to the payload and it can manage several modules at the same time. The Raspberry Pi is used to manage the Arduino, motors, and communicate with the use (see section 6.2). An Arduino is needed for its analog pins which a thermocouple (see section 5.4) will need. A motor controller will also need to be used since the Pi does not have the correct power output to drive the motors. Due to the linear actuator's power requirements and the use of a stepper motor (see section 5.1), a separate motor controller is needed for the linear actuator. A suitable controller for the linear actuator is a TB6600 because it can output 4A of current and can operate a power supply voltage input of 9-42V. For the DC motor in the drill (see section 5.1) and the water pump (see section 4.1) a suitable controller would be a L298N because it can output a current of 2A and can operate with a supply voltage of up to 35V. For wireless communication between the module and HQ, the RFM96W radio transceiver was chosen. It uses the LoRa modulation technique, which encodes information using chirp pulses. This method gives us more range and lower power consumption at the cost of bandwidth, but since the messages are short in length and sent infrequently, this suits our needs. It has a range of about 2km and can reach up to 20km with modified antennas and settings.

Table 10.Communication Module Specifications

Design Specification ID	**Requirement ID Referenced**	**Description**
D5.2.1 A	R6.2.1 A	The communication module will consist of a Raspberry Pi, an Arduino, and motor controllers.
D5.2.2 A	R6.2.3 A	The Raspberry Pi shall communicate with the Arduino and the motor controllers independently.
D5.2.3 A	R6.2.3 A	The communication module shall signal the actuators for the drilling process and the suppression module when either operation is needed to be used.
D5.2.4 A	R6.2.3 A	The DC motor controller shall operate the drill motor and the water pump independently.
D5.2.5 A	R6.2.3 A	The DC motor controller shall have an output of up to 2A and 12V.
D5.2.6 A	R6.2.3 A	Stepper motor controller shall operate the linear actuator.
D5.2.7 A	R6.2.3 A	Stepper motor controller shall have an output of up to 4A and 12V.
D5.2.8 A	R6.2.1 A R6.2.4 A	The communication module shall operate all sensors.

D5.2.9 A	R6.2.1 A	The communication power shall connect power to the sensors.
D5.2.10 A	R6.2.4 A	The communication module shall operate the GPS.
D5.2.11 B	R6.2.4 A	The radio transceiver shall communicate with HQ to a range of 2km.
D5.2.12 B	R6.2.2 B	The communication module shall have a protective shell for heat and external damage.

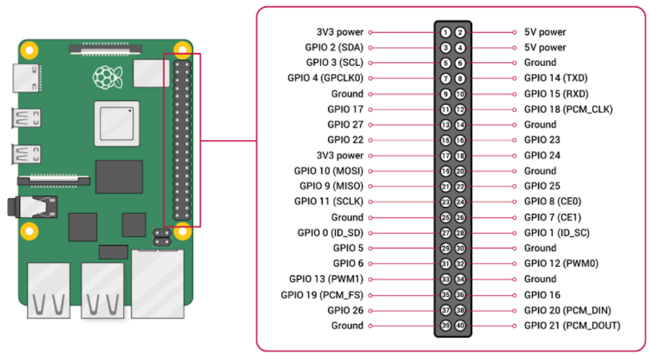

Fig. 2. Raspberry Pi Pins

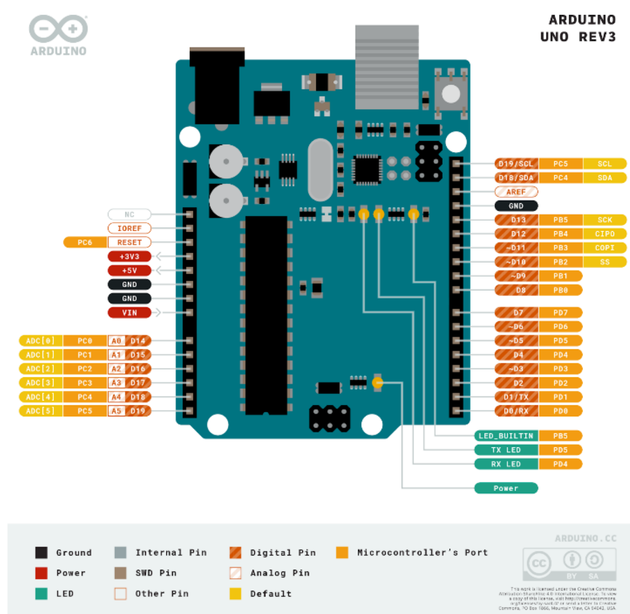

Fig. 3. Arduino Uno Pins

5.3 Camera

The thermal camera is used to detect surface heat to find possible spots of reignition and areas to use the probe. There are drones that are used for monitoring fires which use thermal cameras, some of these cameras are made by FLIR. FLIR has a product line specifically for thermal imaging on drones for monitoring fires. A common resolution in these FLIR thermal cameras is 1280 x 720 [11]. These cameras are around $3000.

Due to constraints in budget, the chosen thermal camera is the AMG8833. The AMG8833 has natural compatibility with the Arduino and Raspberry Pi. It also can measure up to 80°C with an accuracy of ±2.5°C. This should be suitable for the POC as it should still be able to differentiate between embers and other objects.

Table 11. Camera Specifications

Design Specification ID	Requirement ID Referenced	Description
D5.3.1 A	R6.3.1 A R6.3.2 A R6.3.3 A R6.3.4 B	The camera shall be able to output temperature readings to the Raspberry Pi.
D5.3.2 P	R6.3.1 A R6.3.2 A R6.3.3 A R6.3.4 B	The camera shall detect temperature at least 10m away.
D5.3.3 P	R6.3.2 A R6.3.4 B	The camera shall have a resolution of 1280 x 720.
D5.3.4 B	R6.3.5 B R6.3.6 B	The camera shall have a transparent protective shell.
D5.3.5 A	R6.3.4 B	The camera shall be mounted to the front of the UGV.

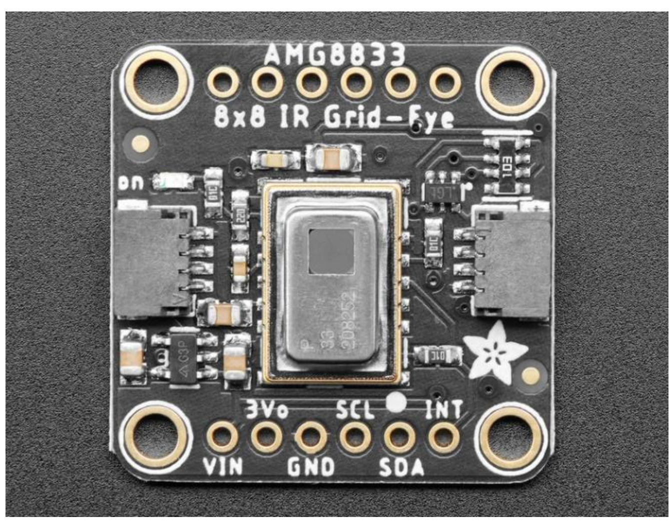

Fig. 4. AMG8833 Thermal Camera

5.4 Probe Temperature Sensor

The probe temperature sensor is used to measure the temperature in the hole that the drill module has dug. It consists of two components working in tandem. The first is a k-type thermocouple to act as the “sensing” part of the two components. On average wildfire temperatures can reach up to 800°C [12]. This type of thermocouple can operate in higher temperatures which will be needed when the probe is being placed underground. Generally, k-type thermocouples operate in the range of -200°C to 1260°C [13]. The second component is a thermocouple amplifier. An amplifier is needed to detect the miniscule resistance changes that are used to measure the temperature. A suitable amplifier is a MAX6675 due to its compatibility with an Arduino.

Table 12. Probe Temperature Sensor Specifications

Design Specification ID	**Requirement ID Referenced**	**Description**
D5.4.1 A	R6.4.1 A R6.4.2 B R6.4.3 A R6.4.5 B	The probe temperature sensor shall measure temperature of up to 800°C.
D5.4.2 A	R6.4.1 A R6.4.5 B	The thermocouple shall be placed in the hole dug by the drill module.
D5.4.3 B	R6.4.1 A R6.4.5 B	The probe temperature sensor shall be lowered into the hole with the drill bit.
D5.4.4 B	R6.4.1 A R6.4.2 B R6.4.3 A	The thermocouple shall operate in temperatures of up to 800°C when underground.
D5.4.5 A	R6.4.1 A	The probe temperature sensor shall operate without the use of an external power supply and directly from the communication module.

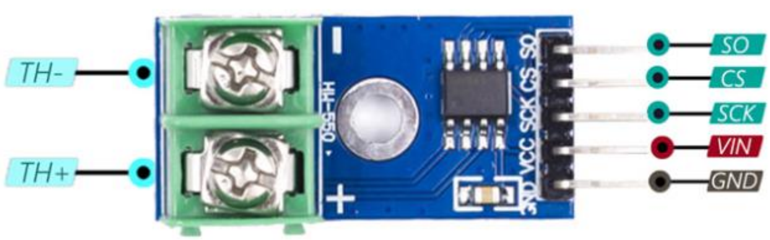

Fig. 5. MAX6675 Module

5.5 Ambient Temperature Sensor

The ambient temperature sensor is used to measure the internal temperature of the module to monitor electronics for overheating. A couple suitable components for the temperature sensor would be the DHT11 and DHT22 sensors. Both are compatible with an Arduino and Raspberry Pi and do not require an external power supply. The sensor should be accurate as temperature maintenance is important for the Ember Trailer’s usage. An accuracy range of ±2°C would be suitable because it would not be way over the limit if it read 2°C above what is desired. The DHT22 is chosen due to its temperature range.

Table 13. Ambient Temperature Sensor Specifications

Design Specification ID	Requirement ID Referenced	Description
D5.5.1 A	R6.5.1 A R6.5.2 B	The ambient temperature sensor shall monitor internal temperature and notify the communication module when temperatures are very high.
D5.5.2 B	R6.5.1 A R6.5.2 B	The ambient temperature sensor shall measure up to 80°C.
D5.5.3 B	R6.5.1 A R6.5.3 B	The ambient temperature sensor shall have an accuracy range of ±2°C.
D5.5.4 A	R6.5.1 A	The ambient temperature sensor shall operate without the use of an external power supply and directly from the communication module.

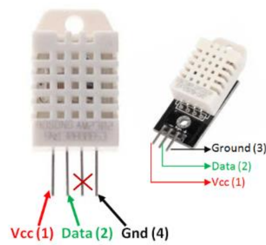

Fig. 6. DHT22 Temperature Sensor (4 Pin and 3 Pin Versions)

5.6 Gas Sensor

The gas sensor measures the CO2 and smoke in the atmosphere. It is used along with the thermal camera to detect hotspots in the area. A suitable sensor would be a MQ135 air quality sensor because of its natural compatibility with the Arduino and Raspberry Pi as well as its ability to measure both CO2 and smoke.

Table 14. Gas Sensor Specifications[2]

Design Specification ID	Requirement ID Referenced	Description
D5.6.1 A	R6.6.1 A R6.6.3 B*	The gas sensor shall measure the CO2 and smoke in the atmosphere.
D5.6.2 B	R6.6.1 A	The gas sensor shall output a ppm value.
D5.6.3 B	R6.6.3 B*	The gas sensors shall accurately measure to ±5% of the theoretical ppm value.
D5.6.4 A	R6.6.1 A	The gas sensor shall operate without the use of an external power supply and directly from the communication module.

[2] * indicates that the requirement phase has been modified as suggested from the feedback received for the Requirements Specifications Document

D5.6.4 B	R6.6.2 B	The gas sensor shall have a protective shell to mitigate heat and external damage.

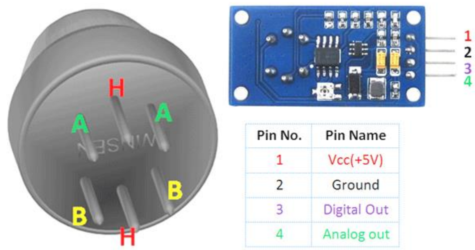

Fig. 7. MQ135 Air Quality Sensor

5.7 GPS Module

The Adafruit Ultimate FeatherWing GPS module was chosen for keeping track of the module and getting location data when hotspots are found. The FeatherWing is compatible with the Arduino and Raspberry Pi, which gives us flexibility on where to mount it. It has a positional accuracy of 3 meters with updates up to 10 times per second, which suits our needs of a low cost, accurate GPS module. However, from initial testing, it seems it only works outside in Vancouver (possibly due to the many tall buildings). We don't expect this to impact performance, as in a real use case, the module would be deployed outside in a remote area without much interference. An option to add a better antenna is also available if needed after the POC and further testing.

Table 15. GPS Module Specifications

Design Specification ID	**Requirement ID Referenced**	**Description**
D5.7.1 A	R6.7.1 A R6.7.4 A	The FeatherWing GPS will detect current location in degrees longitude and latitude within 3 meters accuracy.
D5.7.2 B	R6.7.1 A	The module will update its location at least once per second. (1 Hz)
D5.7.3 B	R6.7.1 A	The GPS will operate without extra external power.

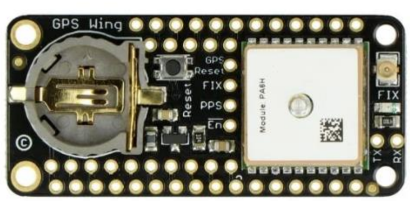

Fig. 8. FeatherWing GPS

6. Software Requirements

6.1 Sensor Data and Hardware Control

The Raspberry Pi will be running a program to collect and analyze sensor data, and to control the suppression and drill mechanisms. The program will be written in Python because of the ease of use and available support from many libraries such as CircuitPython which is used for interfacing with hardware peripherals. OpenCV may be used to analyze thermal images from the camera, which, along with the other sensors, will help identify hotspots. The program will process commands for the suppression and drill mechanisms when they are received. Sensor data will be collected and organized into messages that will be transmitted to HQ, described in section 6.2.

Table 16. Sensor Data and Hardware Control Specifications

Design Specification ID	Requirement ID Referenced	Description
D6.1.1 A	R7.3.1 A	The program for collecting sensor data and controlling the suppression and drill mechanisms will run on the Raspberry Pi.
D6.1.2 A	R6.2.1 A	The Raspberry Pi will collect and analyze data from all sensors.
D6.1.3 A	R6.2.3 A	The Raspberry Pi will send a command to the suppression or drill mechanism when an appropriate message is received from HQ.

6.2 Telemetry

Messages will be transmitted periodically by the Raspberry Pi using a radio transceiver. Another transceiver will be connected to an Arduino, which is connected to the PC at HQ to pass on messages. Due to the low bandwidth of the radio transceivers [14], sending all raw data to HQ would be impossible. To work around this limitation, a limited list of information will be sent by the module. There will be 2 categories of messages transmitted by the Raspberry Pi: status and priority. Status messages will consist of regular updates, sent once per second, that include the module's location, battery level, water level, and ambient temperature. When detecting a hotspot, a priority message will be sent immediately and passed on to responders, informing them of the location and size of the hotspot.

Table 17. Telemetry Specifications

Design Specification ID	Requirement ID Referenced	Description
D6.2.1 B	R7.1.1 B R7.1.2 A R7.1.3 A R7.1.4 A	The Raspberry Pi will communicate with HQ using a long-range radio transceiver [14].
D6.2.2 A	R6.2.1 A	The Raspberry Pi will transmit messages every 1 second.

D6.2.3 A	R6.2.3 A	The status messages will have current location, battery level, water level, and temperature.
D6.2.4 A	R6.2.4 A R7.1.4 A	The priority messages will have the location and size of the hotspot.

6.3 User Application

The user application for Ember Trail will be a standalone Windows program that runs on a PC at HQ. The application will read messages received by the Arduino connected to the PC, and periodically update the information being displayed to the operator, who can pass on the necessary information to responders. The application will also allow the operator to send commands to the module while it is out in the field. These commands will be sent via the connected Arduino using the radio transceiver.

Table 18. User Application Specifications

Design Specification ID	Requirement ID Referenced	Description
D6.3.1 A	R7.3.2 A	The application will be developed as a Windows program.
D6.3.2 B	R7.2.6 B	The application will allow the user to power on/off the module.
D6.3.3 A	R7.2.3 A R7.2.4 A R7.2.5 B R7.2.7 A R7.2.8 A R7.2.9 A	The application will display the module's location, battery level, water level, and temperature.
D6.3.4 A	R7.2.3 A R7.2.4 A R7.2.5 B	The application will periodically update the display with data received from the module.
D.6.3.5 A	R7.1.4 A R7.2.10 A R7.2.11 A	The application will alert the operator when hotspots are detected.
D6.3.6 A	R6.2.3 A R7.1.5 A R7.2.6 B	The application will allow the operator to send a command for power on/off the module.
D6.3.7 A	R6.2.3 A R7.1.5 A	The application will allow the operator to send a command for controlling the suppression mechanism.
D6.3.8 A	R6.2.3 A R7.1.5 A	The application will allow the operator to send a command for controlling the drill.
D6.3.9 A	R6.2.3 A R7.1.5 A	The application will allow the operator to send a command for specifying the drill distance.

7. Conclusion

The design of the Ember Trailer module will follow the specifications detailed in this document during its development in the alpha and beta phase in the next few months. By using 2 different MCUs, the Raspberry Pi and the Arduino, the system will be efficient without sacrificing much quality from its connected components. Therefore, wildfire responders can have accurate information communicated to them, allowing them to respond quicker and make faster decisions based on the data received.

The system is comprised of 3 subsystems:

1. Detection subsystem
    a. Thermal camera
    b. CO^2 sensor
    c. Ambient temperature sensor (to monitor the internal temperature of the system)
    d. GPS (to locate the UGV’s position)
    e. Drilling system
        i. Temperature probe
        ii. Drill motor
        iii. Drill linear actuator
2. Suppression subsystem
    a. Water pump
3. Communication subsystem
    a. Radio transceivers

Although Ember Trailer will observe the specifications as closely as possible, the design is subject to change throughout the development of the product to accommodate a better design to achieve its primary goals.

Product Design Specification Approval

Signature:		**Date:**
Print Name:		
Title:		
Role:		

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Appendix A — User Interface Design

A.1 Introduction

Nature Coolers' product, Ember Trailers, is designed to be used by wildfire responders as they continue the process of quelling a wildfire and preventing a re-ignition of a wildfire. The team is not only dedicated to designing the right thing, but also designing the thing right. Therefore, during both the alpha and beta phase of the product development, tests will be conducted sufficiently for both the hardware and software aspects of Ember Trailer. The hardware design of the module focuses on compactness, usability, and efficiency, as well as how easy it is to attach the module to a drone or UGV. For the software interface that wildfire responders at HQ will be viewing, the goal is to have a readable and familiar interface that would not be difficult to use.

A.1.1 Purpose

This document serves to describe the user interface design for both the hardware and the software components of the Ember Trailer module. It will explain the reasons behind the specific design choices and the justification made for each choice with regards to the prototype of Ember Trailer.

A.1.2 Scope

Detailed within this document will be the following 6 main topics:

1. Graphical Design User Interface
2. User Analysis
3. Technical Analysis
4. Engineering Standards
5. Analytical Usability Testing
6. Empirical Usability Testing

A.2 Graphical Design of the Interface

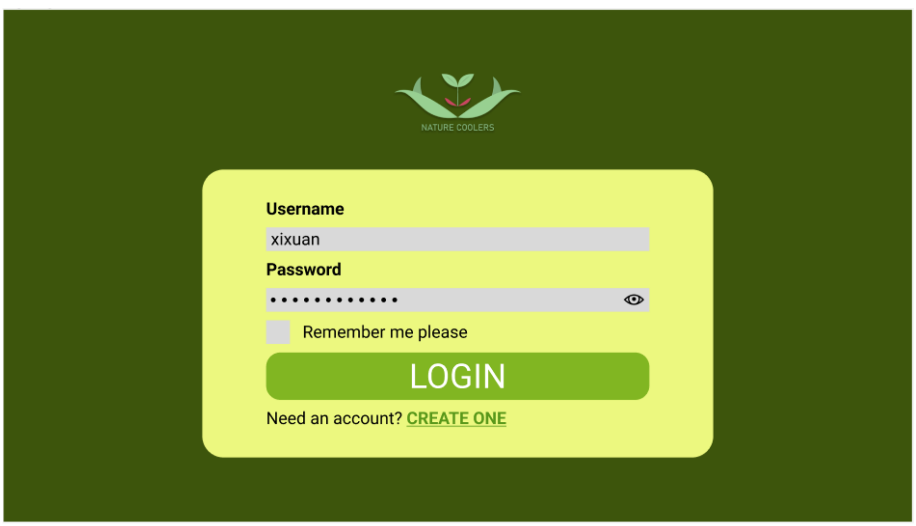

Fig. 9. Login Screen

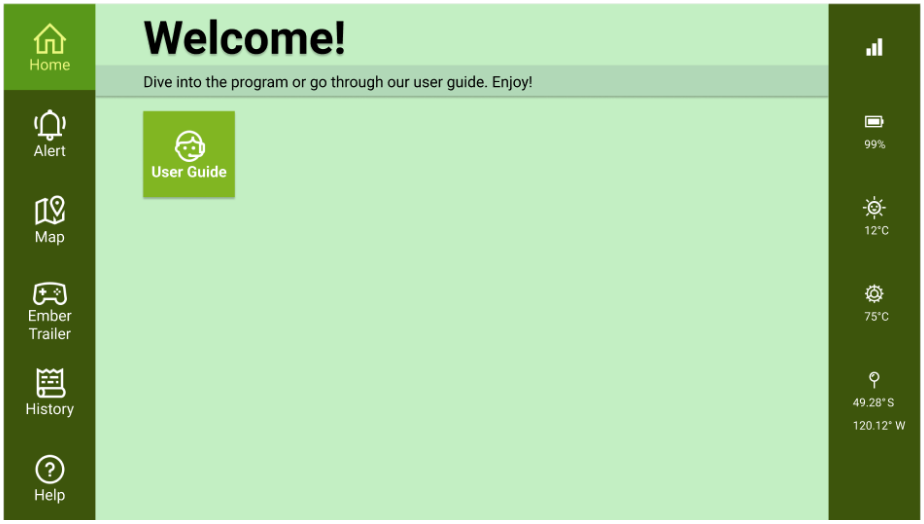

Fig. 10. Welcome Screen

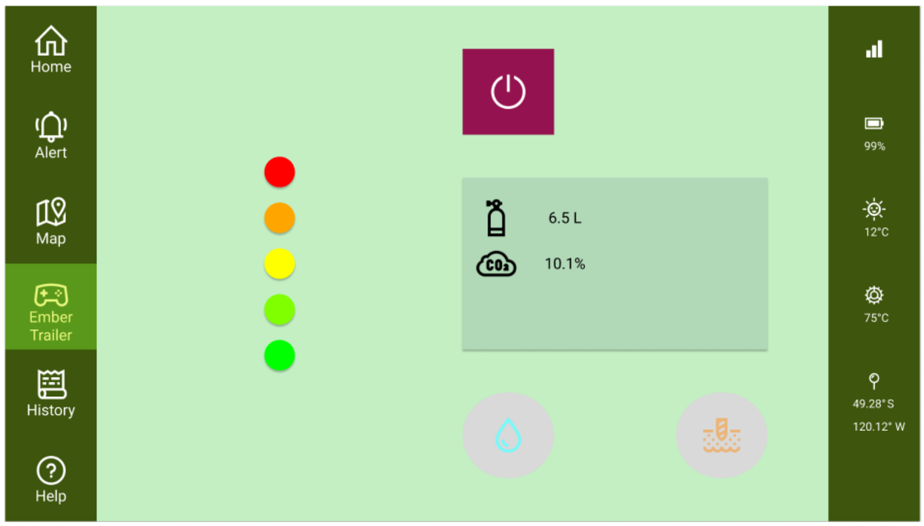

Fig. 11. Main Screen

A.3 User Analysis

Ember Trailer targets a specific market mainly consisting of wildfire responders across the globe. The module can also be used for private property owners that own a part of forested land. Several hypotheses were conceived to elaborate what a user really needs and can expect from this product. Nevertheless, empirical testing must be conducted once the prototype of the module is complete since the hypotheses may not exactly match the requirements of all users. All the hypotheses listed below will be verified and the product will be improved accordingly.

1. We believe that users can quickly find the control panel of the module.
2. We believe that users can understand how to use the program with minimal words.
3. We believe that users are less dependent on interactive guidance.
4. We believe that all users will use metric units.
5. We believe that users usually review program messages and fire alerts before manipulating the module.

6. We believe that users can easily interpret the color connotation of the severity level.
7. We believe that users are not always monitoring the system
8. We believe that users can properly control the module by the app.

A.4 Technical Analysis

In Don Norman's book, "The Design of Everyday Things", he lists seven fundamental design principles to help enhance a user's experience with a product [15]. A description of how Ember Trailer's UI considers each of the seven elements will be detailed below.

Discoverability

Discoverability, also known as visibility, is one of the most crucial components among the other principles, because it directly affects how easily users can locate and navigate the important information. A good user interface design is simple to use, convincing the users to use it time and time again. The minimal design of the interface is at the core of the design. For every page in the program, only necessary information is shown to prevent overload. Only the severity level, control buttons and sensor data is available on that page.

Feedback

The user interface should have an active interaction with its users, by letting them clearly know what actions were taken, what has been completed, and the current status of the system. The current status informs the users, via text, of the various sensors of the module, low battery warning, overheating, and the current position of the module. In addition, when users are operating the module on the "Ember Trailer" page, users need to confirm whether they would like to use drilling or watering functionalities first, then the system will give a notice to users if the module starts doing related actions.

Conceptual Models

Conceptual models offer clear visual metaphors from real life to help users understand the program and what functionalities it can be done with. The big idea of designing the "Nature Coolers Management System" was inspired by car dashboards, where users mainly focus on the speedometer, and occasionally glance at the tachometer and fuel gauge. In this program, as in the similar pattern, users can easily browse main text at the middle portion of the screen, navigate any fire alert, location, history and operate the UGV by clicking corresponding icons at the left-hand side of the screen, as well as monitor the status of the module on the status bar which is situated at the right-hand side of the screen.

Affordances

The affordance refers to how users connect their perceptual knowledge from the real world with the actual actions performed by the program. Nature Cooler Management System provides many familiar icons so that users will not find it difficult to implement desired operations. Moreover, the alert system and rating scale of the fire level also adopt the appropriate color palette. Hence, users can detect the abnormal situations of surroundings and the module timely and simply.

Signifiers

Signifiers tell program developers how to guide a user to reach the correct place to do the correct things effectively. In the Nature Coolers Management System, two vertical lists of intuitive icons distinctly indicate to users where they can operate the module, check alert messages, and view the location of hotspots.

Mappings

An excellent user interface should know how to match greatly between the real world and the program. In this way, users will be more comfortable using the program just like what they do in their real life. As mentioned in section A.3, the developers supposed that users will check the alert message first, then view the map, and finally operate the module. This seems like how an office worker starts his/her new day, checking mails before working. Thus, the developers arrange the options of “Alert, Map and Ember Trailer” from top to bottom.

Constraints
Providing too much flexibility to users is not always a good thing because this will not only increase the memory load of the users, but it is also possible for users to improperly use the program. In the Nature Coolers Management System, users are asked to input their password once more if they have no event in ten minutes to prevent uninvited users from abusing the program. Moreover, for each page of the program, there are only a few buttons available, thereby users are unlikely to confuse which should be the correct button to click.

A.5 Engineering Standards

It is essential for Ember Trailer to adhere to engineering design standards for proper usability. The following table contains published standards that are relevant to the UI design of the product.

Table 19. Engineering Design Standards

Standard	Standard Description
ISO 9241-125:2017	Ergonomics of human-system interaction – Part 125: Guidance on visual presentation of information [15]
ISO 9241-161:2016	Ergonomics of human-system interaction – Part 161: Guidance on visual user-interface elements [16]
ISO/IEC 29138-1:2018	Information technology – User interface accessibility – Part 1: User accessibility needs [17]
ISO/IEC TR 11580:2007	Information technology – Framework for describing user interface objects, actions, and attributes [18]
ISO/IEC 11581-10:2010	Information technology – User interface icons – Part 10: Framework and general guidance [19]
ISO/IEC TR 11581-1:2011	Information technology – User interface icons – Part 1: Introduction to and overview of icon standards [20]
ISO/IEC DIS 23859-1	Information technology – User interfaces – Part 1: Guidance on making written text easy to read and easy to understand [21]
ISO 9241-220:2019	Ergonomics of human-system interaction – Part 220: Process for enabling, executing, and accessing human-centred design within organizations [22]
ISO/IEC/IEEE 26514	Systems and software engineering – Design and development of information for users [23]

A.6 Analytical Usability Testing

For the analytical usability testing, the hard norms should be satisfied to guarantee the reliability and stability of the product. Typically, a heuristic evaluation (detailed in section A.7.1) will be performed a couple of times in the alpha phase, adhering to the engineering standards listed in the previous section and following the user analysis detailed above. This ensures that any design shortage will be found and solved in a timely manner. After each evaluation, the results will be consolidated and discussed before refinements are made. Any critical issues that arise should be completely solved before moving to empirical usability testing.

A.7 Empirical Usability Testing

This usability test focuses on an observational test that is oriented to potential users, if possible, but other participants are still acceptable. Firstly, to receive the maximum rate of investment, 5 participants will be invited to partake in the tests [24]. In addition, an aimful list of usability test tasks will be created to effectively detect the potential deficiency of the module. Then, each participant will be assigned at least one task from the list to perform while one evaluator observes that participant's operations and records any notes. Finally, the participants will be asked to fill in a demographic questionnaire which involves a series of questions such as learnability, accessibility etc. More details on the demographic questionnaire can be found in section A.7.1.

A.7.1 Methods of Testing for Future Implementations

Heuristic evaluation is a checklist to perform an overall test of the module (hardware and software inclusive). The performance of the module is primarily assessed from the 4 aspects: frequency, impact, persistence, and weighting. Frequency measures how often the problem is encountered, impact scales how easy it is to solve the problem, persistence asks how likely it is to encounter the same problem the next time, and weighting analyzes how this problem will impact the market. The template for this evaluation is shown below.

Table 20. Heuristic Evaluation Template

Tester:	**Date:**
Requirement ID #:	**PASS / FAIL** (please circle one)
Name:	
Relevant Heuristic:	
Evidence:	
Detailed Explanation:	
Severity Level (please circle one): 1 – Minor 2 – Major 3 – Critical	

Justification (please choose one before commenting): Frequency (LOW / MID / HIGH):   Impact (EASY / INTERMEDIATE / HARD):   Persistence (ONE-TIME / MULTIPLE-TIME):   Weighting (LOW / MID / HIGH):

The demographic questionnaire concentrates on investigating the degree of satisfaction and the feedback from the participants. This feedback will be considered for future refinements of the product.

Table 21. Nature Coolers' Usability Questionnaire

Questions:	**Rating Scale:** *1 – strongly disagree* *3 – neutral* *5 – strongly agree*				
Overall, I am satisfied using this system	1	2	3	4	5
I felt that using this system is simple	1	2	3	4	5
I was able to complete all the tasks quickly using this system	1	2	3	4	5
I can easily and quickly recover from the mistake I made.	1	2	3	4	5
I can find the information I needed easily	1	2	3	4	5
I am pleased with the interface of this system	1	2	3	4	5
This system possesses all the functions I expect to have	1	2	3	4	5
This system has organized information on its screen	1	2	3	4	5
Extra Comments:					

A.7.2 Safe and Reliable Use of the System

Regarding the safety of the system, all the electronic components will be enclosed and there will be nothing sharp exposed on the module. An ambient temperature sensor will monitor the internal temperature of the system and prevent the module from overheating and causing more issues. At a certain threshold, the module will safely shut down and alert responders that its internal temperature is too high, and it needs to be retrieved a specified location. For the software interface, a login system will be designed to protect any confidential data.

The reliability of the system will include options to cancel suppression and drilling in the case that it was activated accidentally, the UGV needs to evacuate the area, or other similar situations. Additionally, a pop-up message will be displayed to confirm that the user wants to drill into the ground or suppress some embers. An extra feature that will not be included in the prototype but will hopefully be implemented in the future will be the recovery of a forgotten username and password.

Appendix B — Supporting Design Options

B.1 Suppression Module:

Table 22 below outlines the requirements for the suppression module as was detailed in the requirements specification. Table 23 details the design options for the mounting of the hose and nozzle. Table 24 details the design options for the design of the water tank.

Table 22. Requirements for Suppression System

Requirement ID	Description
R5.1.1 B	Suppression hose must extinguish embers
R5.1.2 B	The tank payload must not hinder the UGV
R5.1.3 B	The suppression module shall operate at high temperatures
R5.1.4 A	The suppression hose shall not twist in a way that hinders water flow
R5.1.5 A	The suppression hose shall not extend beyond the UGV's body

Table 23. Design Options for Suppression Mounting

Design Options	Description
U-brackets and screws, wooden mount	Metal U-brackets can be used to fasten the hose to the chassis of any UGV with a flat surface. This method will keep the hose secure and will not prevent flow to the nozzle. A small wooden mount can be built to hold the nozzle and can be fastened with the U-brackets.
3D print casing and screws for hose and nozzle	3D print using ABS to shield and contain the hose, affixing to the UGV with screws. Very flexible option as the shape can be whatever is desired due to 3D printing nature

The first option was selected as 3D printing material may not be strong enough to survive rough terrain and impacts. The high heat the mounting may face could cause the 3D filament to deteriorate faster, thus reducing the lifetime of the module and can be a hazard. U-bracket mounting for hoses are very common and easy to procure. This will also allow the hose to be mounted on the underside of the UGV if necessary. This design option fulfills the requirements for high temperature operation and effective hose mounting.

Table 24. Design Options for Water Tank

Design Options	Description
Wooden box	A tank fashioned from wood in a box shape. Materials are readily available. Slightly heavier but also sturdy and easy to work with if holes need to be drilled for cables and the hose.

Aluminum barrel	Fashioned from aluminum sheets, this material is very lightweight and sturdy. Readily available inexpensively at most hardware stores makes procurement easier. Can be bent to any size and bolted or welded shut. Coated aluminum will not rust when exposed to water for extended periods of time which allows for longer use before a replacement is needed.
Plastic barrel	This design is the most readily available, and lightweight, in many shapes and sizes. Plastic is a poor conductor of heat which will better protect the water and pump inside from the outside heat. The malleability of plastic allows for physical impacts without major damage increasing the life expectancy of the tank.

The third option, the plastic barrel, was selected for the POC as it is the easiest design to acquire and work with. The poor heat conductivity and material flexibility will transfer well into the beta phase of the module. Plastic is the lightest material option which is essential for staying within the theoretical UGV maximum payload of 14kg.
This design option fulfills the requirement of the water tank not hindering UGV operation.

B.2 Drill Module:

Table 25 below outlines the requirements for the drill module as was detailed in the requirements specification. Table 26 details the design options for the linear actuator. Table 27 details the design options for the Drill Motor.

Table 25. Requirements for Drill Module

Requirement ID	Requirement Description
R6.1.1 A	The drill module shall have enough force to drill into the ground.
R6.1.2 B	The drill module shall operate in high temperatures.
R6.1.3 A	The drill module shall not damage the UGV.
R6.1.4 A	The drill module shall not damage the probe sensor.
R6.1.5 B	The drill module shall not interfere with the operation of the UGV.
R6.1.6 A	The drill module shall not interfere with the operation of Ember Trailer.

Table 26. Design Options for the Linear Actuator

Design Options	Description
Rail Stepper Motor	Commonly used in CNC machines. There is a mounting bracket on the rail and it does take up too much space relative to its stroke. Highly accurate.

Cylindrical Rod	Commonly used general linear actuator. Has high speed and force, and something can be mounted at the end of its rod. At full stroke length, the actuators' full length is about double its stroke length. It is quiet and can carry a heavy load.

The first option is chosen due to its accuracy and size. The cylindrical rod linear actuator is much too long in length for our module to carry and it will be more complicated to mount the drill to it. For the stepper motor in the linear actuator a common one is a NEMA23.

Table 27. Design Options for the Drill Motors

Design Options	Description
DC Motor	Simple and commonly used for a variety of projects, and they are used in drills. They provide continuous rotation until power is not given. DC motors can provide a wider range of options for speed and torque.
Servo Motor	Composed of four components: a DC motor, gear set, control circuit, and position sensor. They cannot rotate freely. The angle of rotation is limited. They can be very fast and provide high torque.
Stepper Motor	Composed of multiplied toothed electromagnets surrounding a gear for positioning. They provide slow, accurate positioning as well as a constant holding torque. More complicated to set up compared to a DC motor, and it requires more GPIO pins from the controller.

The DC motor is chosen due to its simplicity, speed and torque. The servo motor does not have a continuous motion, therefore it's a poor choice for a drill. The advantages of the stepper motor are not needed for the drill.

B.3 Communication Module:

Table 28 below outlines the requirements for the communication module as was detailed in the requirements specification. Table 29 details the design options for the microcontroller. Table 30 details the design options for the stepper motor controller. Table 31 details the design options for the DC motor controller. Table 32 details the design options for the radio transceiver.

Table 28. Requirements for Communication System

Requirement ID	Requirement Description
R6.2.1 A	The communication module shall gather data from all sensors and the camera.
R6.2.2 B	The communication module shall operate in high temperatures.
R6.2.3 A	The communication module shall accept inputs from the user.
R6.2.4 A	The communication module shall output data to the user.

Table 29. Design Options for Microcontroller

Design Options	Description
Raspberry Pi	A common controller for robotic applications. Can handle operating multiple tasks at once and complicated code. There are many GPIO pins to use for all electronic parts as well as four USB options and WiFi.
Arduino	A simple controller with both analog and digital pins. There is a lot of information for various projects online for this controller. However, it may not be able to handle everything that is needed to work for the Ember Trailer

We have chosen to use both options for various modules of the Ember Trailer. However, the Raspberry Pi will act as the primary controller, while there will be two Arduinos used for specific purposes, and these are connected to the Pi.

Table 30. Design Options for the Stepper Motor Controller

Design Options	Description
TB6600	A commonly used stepper motor driver, specifically used for the NEMA 17 and NEMA 23 motors. It can output up to 4A. The power supply used can be from 9-42V.
DM542T	Another commonly used motor driver, specifically used for the NEMA 14, 17, 23, 24. It can output 4.2A. The power supply used can be from 8-45V.
G540	Premium option that can operate 4 stepper motors. It can output up to 3.5A. The power supply used can be from 18-50V.

The first option is selected because it is commonly used for the NEMA 23 motors (see section B.2) and it can output the right amount of current and voltage for the linear actuator. The DM542T is slightly more expensive, but can output slightly more current and voltage, however that is not needed. The G540 is much too expensive, and we don't need to control more than one stepper motor.

Table 31. Design Options for the DC Motor Controller

Design Options	Description
L298N	Common motor driver compatible with Raspberry Pi and Arduino MCUs. Able to control 2 DC motors or 1 stepper motor. Can provide drive voltage between 7-35V with a current of 2A per motor. Very accessible design, no soldering required to use.
TB6612	Compatible with Raspberry Pi and Arduino controllers. Can drive 2 DC or 1 stepper motor. Provides drive voltage of 4.5-13.5V with a drive current of 1.2A. Sleek, low-profile design that may require soldering to use.

The first option was selected because of the higher drive current. This driver is used to manage the water pump and the DC motors in the drill module. Both require 12V power and the water pump is rated 1.5A so the TB6612 may not run it desirably. The L298N also uses phoenix connectors which makes it easier to work with while the TB6612 will require soldering.

Table 32. Design Options for the Radio Transceiver

Design Options	Description
nRF24L01	2.4 GHz transceiver. It can transfer up to 2Mbps for about 100 meters. Can pair to 6 other modules. High speed, but low range and requires pairing and high-power consumption to maintain connection.
RFM96W	433 MHz transceiver. It can transfer up to 19Kbps for 2km. No pairing process and unlimited other modules. Simpler listener/sender format. Low speed, but high range and low power consumption.

The RFM96W was chosen because of its high range which is necessary for the large outdoor environments where the module will be used. Because of the fast-processing power of the Raspberry Pi, we can analyze the sensor data directly on the module, and only send periodic, compressed messages, which will save bandwidth. Because of the simpler receiver/sender connection, we save power on not having to maintain connections and can have many modules sending data to HQ if we decide to add more after the POC.

B.4 Camera:

Table 33 below outlines the requirements for the camera as was detailed in the requirements specification. Table 34 details the design options for the camera.

Table 33. Requirements for the Thermal Camera

Requirement ID	Requirement Description
R6.3.1 A	The camera shall be able to detect heat radiating off an object.
R6.3.2 A	The camera shall be able to distinguish between various objects.
R6.3.3 A	The camera shall be able to distinguish different temperature readings.
R6.3.4 B	The camera shall have sufficient field of view to see the desired area.
R6.3.5 B	The camera shall operate in high temperatures.
R6.3.6 B	The camera shall be protected from external physical damage.

Table 34.Design Options for the Camera

Design Options	Description
MLX90640	Sensor has a 24x32 array of IR thermal sensors. Can measure a temperature range of -40℃ to 300℃ with an accuracy of ±2℃.
AMG8833	Sensor has a 8x8 array of IR thermal sensors. Can measure a temperature range of 0℃ to 80℃ with an accuracy of ±2℃.

Note: This table is specifically for the POC because the options for higher resolution cameras are expensive, about 3000$, and out of budget. However, FLIR does provide thermal cameras that could be used for the final product (see section 5.3).

The second option is chosen despite its inferior technical specifications because the MLX90640 is more expensive than the AMG8833. And there is no need for better specifications, if the specifications are good enough, when it would be replaced with a much more powerful camera for production.

B.5 Probe Temperature Sensor:

Table 35 below outlines the requirements for the probe temperature sensor as was detailed in the requirements specification. Table 36 details the design options for the detecting underground embers.

Table 35. Requirements for Probe Sensor

Requirement ID	Requirement Description
R6.4.1 A	The probe temperature sensor shall measure the temperature of the ground.
R6.4.2 B	The probe temperature sensor shall operate in high temperatures.
R6.4.3 A	The probe temperature sensor shall give accurate readings.
R6.4.4 B	The probe temperature sensor shall withstand external pressure.
R6.4.5 B	The probe temperature sensor shall withstand pressure while being driven into the ground.

Table 36. Design Options for Detecting Underground Embers

Design Options	Description
Probe Sensor	A short probe that can be inserted into dirt or liquids and will return a temperature reading. Can be mounted anywhere due to its small and lightweight nature. Does not have to remain static, the probe can be maneuvered easily. Uses change in resistance of its surroundings to return usable temperature information.

Infrared Sensor	A handheld device to check the temperature of a surface at a distance. Uses an infrared beam to measure temperature. Comes in smaller, accessible forms as well, for easy connection to an MCU. Does not need to be moved to obtain an accurate reading.

The first design option was chosen for the POC model. In the field, there will be plenty of dirt and debris that will cover the sensor which would negatively impact the operation of the IR sensor. The probe will not suffer the same because once it's inserted into the ground, the debris covering it will heat to the same temperature as the surrounding ground, giving a more accurate reading.

B.6 Ambient Temperature Sensor:

Table 37 below outlines the requirements for the ambient temperature sensor as was detailed in the requirements specification. Table 38 details the design options for the thermocouple. Table 39 details the design options for the thermocouple amplifier.

Table 37.Requirements for Ambient Temperature Sensor

Requirement ID	Requirement Description
R6.5.1 A	The ambient temperature sensor shall measure the internal temperature of the module.
R6.5.2 B	The ambient temperature sensor shall operate in high temperatures.
R6.5.3 A	The ambient temperature sensor shall give accurate readings.

Table 38. Design Options for the Thermocouple

Design Options	Description
DHT11	Small temperature sensor that can be plugged directly into a circuit board. Operating at 3-5V and 2.5mA max current draw when in use. This sensor is good for temperature measurements of 0-50℃.
DHT22	Small temperature sensor that can be plugged directly into a circuit board. Operating at 3-5V and 2.5mA max current draw when in use. This sensor is good for temperature measurements of -40-80℃.

The second design option was selected due to the sensing range. Both sensors are from the same manufacturer, so the operating specs are the same but the DHT22 has a wider range of sensing for temperature. It works at half the speed of the DHT11 but when dealing with embers, having a sensor that can detect higher than 50℃ is far more useful than the speed factor.

Table 39. Design Options for the Thermocouple Amplifier

Design Options	Description
MAX6675	Cold Junction Compensated K-Thermocouple to Digital converter. 12-bit, 0.25℃ resolution. Only works with K-type thermocouples. Uses SPI protocol for communication with MCU. Has libraries set up for use on an Arduino board.
MCP9600	Thermocouple to Digital converter amplifier. Works with many different types of thermocouples. Uses I2C communication protocol for connection to MCUs. Very high-resolution converter.

The first option was chosen due to the ease of use. The MAX6675 uses SPI which is extremely easy to set up with an Arduino board compared to I2C, which is slightly more complex. Additionally, there are some Arduino libraries set up for this converter which adds to the ease of use.

B.7 Gas Sensor:

Table 40 below outlines the requirements for the gas sensor as was detailed in the requirements specification. Table 41 details the design options for the gas sensor.

Table 40. Requirements for the Gas Sensor

Requirement ID	Requirement Description
R6.6.1 A	The gas sensor shall measure the gas concentration in the surrounding atmosphere.
R6.6.2 B	The gas sensor shall operate in high temperatures.
R6.6.3 A	The gas sensor shall give accurate readings.

Table 41. Design Options for the Gas Sensor

Design Options	Description
MQ-135	Air quality sensor that detects ammonia, sulfide, smoke, and other harmful gases. Easily integrable with an Arduino or Raspberry Pi board. Can provide both a digital and analog output.
SEN0127	Gas sensor that can detect methane, hydrogen, smoke, and many other gases. Primarily integrable with Arduino boards. Provides only an analog output.

The first option was chosen due to its easy integration and flexibility. The ability to effectively connect the MQ-135 to either type of MCUs allows us flexibility with the other sensors and actuators. Ideally, a digital reading is desired for maximum accuracy which places the MQ-135 automatically above the SEN0127.

B.8 GPS Module:

Table 42 below outlines the requirements for the GPS module as was detailed in the requirements specification. Table 43 details the design options for the GPS module.

Table 42. Requirements for GPS Module

Requirement ID	Requirement Description
R6.7.1 A	The GPS module shall transmit the UGV's location in longitude and latitude format.
R6.7.2 A	The GPS module shall transmit the location when the conditions for a fire have been met.
R6.7.3 B	The GPS module shall operate in high temperatures.
R6.7.4 A	The GPS module shall transmit accurate coordinates.

Table 43. Design Options for the GPS Module

Design Options	Description
L80-M39	GPS module with accuracy of 2.5m, 33s start time, 3.3v at 20-25mA power consumption.
FGPMMOPA6H (Featherwing)	GPS module with accuracy of 3m, 34s start time, 3.3v at 30-35mA power consumption. Optional battery to speed up start time.

The two GPS modules have similar specs, with the FeatherWing having slightly less accuracy and more power consumption. It does have a battery in case the module needs to reboot in which it will reacquire its location faster. Overall, the difference in specifications doesn't make that much of a difference so we chose the FeatherWing for its lower cost and availability.

B.9 User Application:

Table 44 below outlines the requirements for the user application taken from the requirements specification. Table 45 details the design options for the user application.

Table 44. Requirements for User Application

Requirement ID	Requirement Description
R7.2.1 B	The program will ask the user for credentials after idling for 10 minutes to prevent unauthorized access.
R7.2.2 B	The program must have color and font size options for the visually impaired.
R7.2.3 A	The program must represent the current volume of the battery.
R7.2.4 A	The program must display the location of the module.
R7.2.5 B	The program will display a map highlighting hotspots, extinguished hotspots, and the UGV/module position.
R7.2.6 B	The program must have controls for power on/off the module.
R7.2.7 A	The program must display a warning when the battery level falls below 15%.
R7.2.8 A	The program must display a warning when the equipment is overheating.
R7.2.9 A	The program must display a warning with the last known location when the signal is lost and attempt to reconnect.
R7.2.10 A	The program must inform the field team the specific orientation in longitude and latitude when the module detects a potential wildfire.
R7.2.11 A	The program must inform the field team the specific orientation in longitude and latitude when the module detects surface or subterranean embers.
R7.3.2 A	The HQ software must be able to run on a basic computer.

Table 45. Design Options for the User Application

Design Options	Description
Desktop application	Stand-alone program that will be accessible on computers that have it installed. It can be accessed offline and can provide faster performance.
Web application	A web application will allow remote access, provided the user has internet access. Access will not be restricted to specific devices.

For the user application, we have decided to use a desktop application for its simplicity and convenience, while still being able to satisfy all the requirements.

Appendix C — Supporting Test Plans

In the following sections, supporting test plans are provided in addition to the acceptance test plan from the requirements specifications document [2]. Addressed are tests for the design of the system as well as the 3 subsystems of Ember Trailer. The criteria highlighted in yellow are requirements that should be satisfied by ENSC 405W end-of-term demonstration.

C.1. General System Testing

General System Test Sheet

Company 3 — Nature Coolers Date:

Mounting onto the UGV	
Does not inhibit UGV operation ☐ Yes (pass) ☐ No (fail)	Comments:
Tightly mounted ☐ Yes (pass) ☐ No (fail)	
Software Components	
Operator can send command from HQ to power on/off the module ☐ Yes (pass) ☐ No (fail)	Comments:

C.2. Detection Subsystem Testing

Detection Subsystem Test Sheet

Company 3 — Nature Coolers Date:

Hardware Components	
Drill Module	Comments:
Penetrates the ground ☐ Yes (pass) ☐ No (fail)	
Only minimally displaces the UGV if displaces at all ☐ Yes (pass) ☐ No (fail)	
Extends and retracts with no issue ☐ Yes (pass) ☐ No (fail)	
Thermal Camera	Comments:
Detects temperature: ≥10m ☐ Yes (pass) ☐ No (fail)	
Temperature Probe	Comments:
Measures temperature: ≤800°C ☐ Yes (pass) ☐ No (fail)	

Enters hole made by the drill module ☐ Yes (pass) ☐ No (fail)	
Ambient Temperature Sensor	Comments:
Measures temperature: ≤100°C ☐ Yes (pass) ☐ No (fail)	
Accuracy: ±2°C ☐ Yes (pass) ☐ No (fail)	
Gas Sensor	Comments
Measures CO^2 ☐ Yes (pass) ☐ No (fail)	
Measures smoke ☐ Yes (pass) ☐ No (fail)	
GPS Module	Comments:
Location updated at least once per second ☐ Yes (pass) ☐ No (fail)	
Accuracy: ±3m ☐ Yes (pass) ☐ No (fail)	
Software Components	
Drill receives command from operator to activate/deactivate and drill a specified distance ☐ Yes (pass) ☐ No (fail)	Comments:
User Interface	Comments:
Displays location, battery level, water level, temperature ☐ Yes (pass) ☐ No (fail)	
Display updates periodically ☐ Yes (pass) ☐ No (fail)	
Alerts when a hotspot is detected ☐ Yes (pass) ☐ No (fail)	

C.3. Suppression Subsystem Testing

Suppression Subsystem Test Sheet	
Company 3 — Nature Coolers	Date:

Mechanical Components

Suppresses embers from beneath the UGV ☐ Yes (pass) ☐ No (fail)	Comments:
Effectively pumps the suppressant ☐ Yes (pass) ☐ No (fail)	
Software Components	
Activates/deactivates according to a command from the operator ☐ Yes (pass) ☐ No (fail)	Comments:

C.4. Communication Subsystem Testing

Communication Subsystem Test Sheet

Company 3 — Nature Coolers Date:

Hardware Components	
Operates all sensors from HQ ☐ Yes (pass) ☐ No (fail)	Comments:
Operates drill component from HQ ☐ Yes (pass) ☐ No (fail)	
Operates suppression component from HQ ☐ Yes (pass) ☐ No (fail)	
Software Components	
Collects data from all sensors ☐ Yes (pass) ☐ No (fail)	Comments:
Receives messages from HQ ☐ Yes (pass) ☐ No (fail)	
Sends commands to suppression mechanism ☐ Yes (pass) ☐ No (fail)	
Sends commands to drilling mechanism ☐ Yes (pass) ☐ No (fail)	
Sends sensor data to HQ ☐ Yes (pass) ☐ No (fail)	
Transmission rate: 1s ☐ Yes (pass) ☐ No (fail)	
Little to no messages are dropped ☐ Yes (pass) ☐ No (fail)	
Operator can send a command to activate/deactivate the drill	

☐ Yes (pass) ☐ No (fail)	
Operator can send a command specifying drill distance ☐ Yes (pass) ☐ No (fail)	
Operator can send a command to activate/deactivate the suppression mechanism ☐ Yes (pass) ☐ No (fail)	