ROBO050

Design and Development of an Autonomous Wildfire Suppression Firefighting Robot

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Engineering Problem & Objectives

Problem Statement: Wildfires are the most destructive and costly emergencies to respond to. They erratically spread and can destroy wildlife and populated regions quickly. Unlike urban environments, where buildings have been designed with fire engineering in mind, vegetation covered land has nothing of the sort, and thanks to this, early stage intervention is critical. However, current systems are largely reactive rather than proactive. At the present, there is minimal real time surveillance or early warning coverage across forests and wildland areas, and fire response typically starts after the event has been reported. By the time proper surveillance has been conducted and resources have been diverted to the fire, it may have already grown rapidly. This delay drives up both the scale of response and the associated cost. Additionally, the resources that are allocated are extensive, including engines, aircrafts, and personnel that can cost hundreds of dollars an hour but more importantly, divert resources from the rest of a city that is now devoid of fire personnel.

My approach : I want to design a Fire resistant Hardware / Software platform that can be used to build a robot that actively tracks and extinguishes flames in its proximity using AI image detection features. I am experimenting with various different materials that have different properties that allow it to resist heat, whether they be insulating properties, or absorbing properties. To conduct this experiment, I first developed a testing fire box in which I aimed a precision torch that could heat a spot of the box to hundreds of degrees, and then protected the box with the different materials, seeing how long that it would take the thermocouple inside of the box to reach 50ºC, the failing temperature for electronics that would be inside a robot.

Work by others - Work by others has involved either developing the software platform as proof of concept[1,2] or commercial ventures[3,4,5,6] that are piloted remotely or through aerial surveillance[7]. I wanted to create a prototype which could detect locally, make a decision to suppress and also be able to sustain high temperatures for a reasonable time using multiple sensor inputs (thermal, physical, ambient and optical signals) I have been doing projects that relate to the field of autonomous vehicles for a 3 years now, but past years' project have been about sensors and data collection, and software side of autonomous vehicles and this year I have created a prototype that can detect and extinguish fire and reduce human risk and suppress wildfires before they spread.

Design Constraints

In this project, I have several constraints to consider while designing my autonomous fire detection system as listed below:

1. Operating temperature
2. Maintaining visibility of the area of interest for accurate navigation
3. Multisensor input based decision making
4. Communication Failure
5. Unknown terrain

However I still believe that if a robot can replace a human in dangerous environments, it is worth the effort and time

Path to an Autonomous Firefighting Robot

The work was divided into 2 Phases: Phase A: Thermal Protection Phase B: Robot Platform Development

Phase A - Methods - Thermal Protection

Round 1: Individual Material Tests

The first round was used to test the thermal performance of candidate materials[7] individually to establish a baseline and screen for the most effective insulators.

1. *Baseline Control:* The test rig was heated with no internal insulation. This provided the control data to measure the time required for the internal temperature to reach 50°C in the uninsulated tin.
2. *Individual Material Tests:* Individual samples of the following materials were placed outside the test rig and exposed to the heat source, while inserting the thermocouple in three different positions.
   - Ceramic Fiber Blanket
   - Aerogel Blanket
   - Carbon Felt
   - Fiberglass Heat Shield
   - Heat Blocking Putty

Based on the performance of the individual materials, the second round focused on testing composite stacks designed to achieve the objective of maintaining an internal temperature under 50°C to the lowest possible value.

Round 2: Best Configuration Testing

Based on the performance of the individual materials, the second round focused on testing composite stacks designed to achieve the objective of maintaining an internal temperature under 50°C to the lowest possible value.

The following multi-layer configurations were tested for a 10-minute duration:

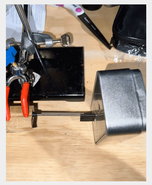
- Bilayer Configuration: Heat Blocking Putty + Ceramic Fiber Blanket.
- Trilayer Configuration: Fiberglass Heat Shield + Ceramic Fiber Blanket + Heat Blocking Putty.

The goal of this phase was to identify the material combination with the lowest rate of temperature rise (dT/dt), indicative of the lowest thermal diffusivity.

Phase A - Materials Properties

#	Material Used	Purpose	Material Type	Density (g/cc)	Thickness	Thermal Conductivity
1	Tin container	Enclosure	Tin coated (<2um) steel	7.85	0.1	Tin container
2	Ceramic Fiber Blanket	Insulator	Aluminum Silicate Fiber	0.064 - 0.160	25.1	Ceramic Fiber Blanket
3	Aerogel Blanket	Insulator	Nanoporous silica aerogel reinforced with fiberglass	0.18 - 0.22	10.2	Aerogel Blanket
4	Dobtim Pipe Wrap	Reflective Insulator	Fiberglass wrap	0.88	1.1	Fiberglass Heat Shield
5	Heat Blocking Putty	Heat absorber	Hydrogel ceramic composite	1.05	4	Heat Blocking Putty
6	Carbon Felt	Insulator	Carbon felt	0.09	3.1	Carbon Felt

Phase A - Set up



Thermocouple setup



Thermocouple Thermometer



Surface Damage Comparison

All images taken by Finalist, 2026.

Phase A - Single Layer Candidate Materials



Heat Blocking Putty



Ceramic Fiber Blanket



Fiberglass Heat Shield



Carbon Felt



Aerogel Blanket

All images taken by Finalist, 2026.

Phase A - Bilayer and Trilayer Constructions



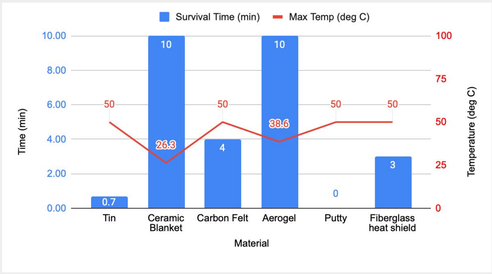
Bilayer - Heat Blocking Putty & Ceramic Fiber Blanket

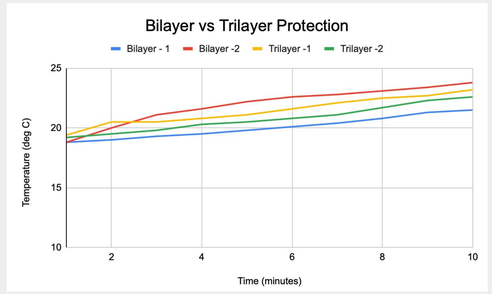


Trilayer - Heat Blocking Putty, Ceramic Fiber Blanket & Fiberglass Heat Shield

Both images taken by Finalist, 2026.

Phase A - Results- Thermal Protection





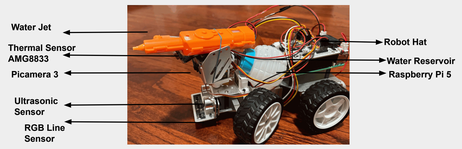
Both graphs created on Google Sheets by Finalist, 2026.

The baseline control test demonstrated the need for insulation, as the uninsulated tin container reached the 50°C safety limit within 0.70 minutes.
Ceramic Fiber Blanket and Aerogel Blanket performed the best

Performance Comparison (10 minute test):

- Ceramic Fiber Blanket showed the strongest performance, with the internal temperature rising only 8.3°C over 10 minutes (Final Temp: 26.3°C).
- Aerogel Blanket: Also survived the 10 minute test, but recorded a higher total temperature rise of 18.5°C (Final Temp: 38.6°C).
- Rapid Failures: Carbon Felt, Fiberglass Heat Shield.
- Heat Blocking Putty- The material burnt and fell off, yielding no usable data for the full 10 minute test.

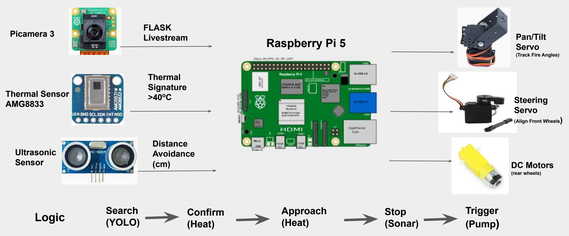
Phase B - Method - Robot Platform Development



Fire Fighting Robot with all sensors. Image taken by Finalist. Labeling done in Google Slides, 2026.

Phase B - System Architecture Diagram

This diagram shows how the "Brain" (Raspberry Pi 5) coordinates the "Senses" (Camera, Thermal, Sonar) to control the "Muscles" (Motors and Servos). Robot Platform Development image created by Finalist using Google Slides, 2026.



Phase B - Robot Logic & Data Flow

1. Search Phase: The Pan Servo sweeps the camera left and right until YOLO sees a "Fire" bounding box.
2. Verification Phase: The Pi checks the AMG8833 Thermal Array. If the heat at that same angle is >40◦C, it confirms the target is real.
3. Approach Phase: The Steering Servo aligns the wheels with the camera angle, and the DC Motors move the robot forward.
4. Safety Phase: The Ultrasonic Sensor constantly monitors distance. If the robot gets within 20 cm of an object, it stops to avoid a collision.
5. Trigger Phase: The positive fire detection triggers the water pump to dispense

Phase B - Results - Power Modeling

$$T(M,S) = \frac{C}{P_{const} + (I_m \cdot M) + (I_s \cdot S)}$$

Temperature increase as a function of time

$$T(t) = 0.378t + 18.5$$

From that, time taken to reach a temperature

$$t(T) = \frac{T - 18.5}{0.378}$$

$\mathrm{T(M,S)}$ = Battery Life (minutes) in terms of motor usage and servo usage

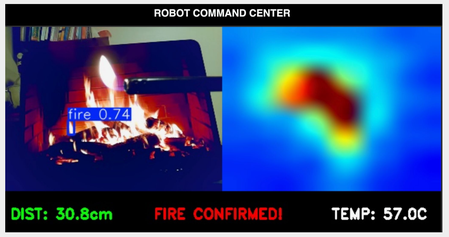
C = Battery Capacity

$\mathrm{P_{const}}$ = Constant power used by pi and sensors

$\mathrm{I_M/I_S}$ = Maximum current draw for motors and servos

Using the temperature increase equation derived from the trilayer data, it will take 83.33 minutes for the box to reach 50º C. The time that the robot can operate is limited by whichever function provides a shorter time frame. From testing the power consumption of the robot, I was able to estimate an approximate 2.1 percent battery lost per minute, leading to a 41.6 minutes battery life, however this is subject to change with power consumption.

Phase B - Results - Fire Detection & Confirmation



Screenshot taken by Finalist, 2026

In this image capture, I am demonstrating the capture of fire on a lighter and fire image on an ipad. The high temperature is flagged as a fire confirmed. I am measuring accuracy and reliability of the detection algorithm in parallel and data is currently being reviewed

Discussion

The project was successful in detecting fire using the thermal camera and ultrasonic sensor. The YOLO 8 onboard AI model successfully labelled any fire image as a fire but did not trigger the fire active alarm due to the additional logic of temperature. The program is supposed to follow the logic of sense, think, act sequence. I have managed to create the sense and think aspect at the time of this report. I will continue to improve the model and the software architecture to trigger a water dispense signal as the next step. The Hardware / Software / Thermal Protection platform can be expanded to large size vehicles or small size rovers for fire fighting; I also envision my technology being used by designers of urban spaces that are close to wildfire prone zone. I am truly excited at the prospect of exploring where my project goes in the future!

Challenges Faced

- Color channel conflict:: My fire image appeared deep blue initially. This was due a conflict between Pi 5 camera capture and YOLO /Open CB library code. I had to implement a channel flip for the AI to capture red signature of the fire.
- I faced several issues with recurring attributeerror crashed due to the library version conflicts in the picarx library. I had to implement the Python hasattr() function to get distance which kept changing between get_dist(), get_distance(), and read().
- Burning smell: Due to a high current draw of the motor in combination with the pi 5 causing a burning smell. I switched to a MOSFET module to physically separate the pump from the Pi to create a high-power switch.
- Performance & Frame Rate was very laggy due to YOLO ML bandwidth along side Flask and I2C data load. The detection was very jerky and laggy. I fixed this by reducing the image size for AI analysis and also implemented switching between sensor reads and video / fire detection.
- Pump Installation challenges: Due to lack of time, I bought an off the shelf water pump with a nozzle sprayer to mimic fire extinguishing media. I had to disassemble the pump assembly and rewire it to my pi Hat to enable control from the robot. The pump dispense sequence was very challenging.
- Overall mechanical stability and reliability: I put more focus on software/hardware (SW/HW) platform development and used off the shelf kit to improvise my robot assembly. I observed some mechanical instabilities in the process. I also faced issue of constantly running out of power due to the processing and compute slowing down the overall development.
- Accuracy and Statistical Data Analysis: I really wanted to collect confidence level of the AI detection as well as accuracy data of successful fire extinguishing instances in a controlled environment. This is still work in progress,

Innovation

Key Innovation in the project:

- Platform Development: The project was successful in detecting fire using the thermal camera and ultrasonic sensor. The YOLO 8 onboard AI model successfully labelled any fire image as a fire but did not trigger the fire active alarm due to the additional logic of temperature. The software SW also communicated with the sensors. Motors, servo and the pump to make a decision on triggering the pump to dispense water from a safe distance (decision making using distance sensor). I successfully developed a test bed which can be used to develop a full scale AI firefighting robot. I built the brains needed for such an endeavor
- Protecting the circuits: I also created a materials database to find out a set of materials that would potentially save my circuits from burning out. The logic of working backwards from safe operating temperature and maximum allowable time, By testing the power consumption of the robot, I was able to estimate an approximate 2.1 percent battery lost per minute, leading to a 41.6 minutes battery life, however this is subject to change with power consumption.

Real World Challenges

During the course of my project, I spoke with Robert Colbertson, Battalion Chief at the San Jose Fire Department. The discussion opened my eyes to the real-world challenges of firefighting and the vicious nature of forest fires. In his own words, the key challenges faced by the firefighting department were twofold: "Lack of reliable real-time surveillance" and " the extreme resource drain a forest fire puts on the department, which impacts several other emergencies that need attention." There was a clear need for automation, surveillance, and quick response, which would save hundreds of thousands of dollars and human resources on the ground.

Conclusion

A primary goal of mine to incorporate into this project is the future investigation of fire resistant hardware design. Due to the fact that standard plastic and other materials that sensors are made from are susceptible to heat, and fireproofing the sensor can interfere with the logic and computation, I wish to develop a novel way to counteract this issue. The next iteration of the robot will incorporate my findings and development in thermal insulation onto the body of the firefighting robot, as well as include a custom-engineer enclosure to better include these materials that will heat shield the raspberry pi and sensitive electronics from heat. Also, to enhance durability as well as mobility, I plan on transitioning from plastic and rubber transport components that I am using to metal link tracks, which are designed to withstand extreme heat and also navigate rough terrains that are present in forest fire areas that regular wheels may get stuck in.
Additionally I will explore active cooling methods in order to extend the operational lifetime that the robot will be able to withstand flames and suppress them. By implementing a system to cool the internal electronics of the robot, their lifespan will become inconsequential.

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