INDIAN INSTITUTE OF TECHNOLOGY ROPAR

“DEVELOPMENT OF FIRE FIGHTER BOT”

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ABSTRACT

A fire incident is a disaster that can potentially cause the loss of life, property damage and permanent disability to the affected victim. They can also suffer from prolonged psychological and trauma. Fire fighters are primarily tasked to handle fire incidents, but they are often exposed to higher risks when extinguishing fire, especially in hazardous environments such as in nuclear power plants, petroleum refineries and gas tanks. They are also faced with other difficulties, particularly if a fire occurs in narrow and restricted places, as it is necessary to explore the ruins of buildings and obstacles to extinguish the fire and save the victim. With high barriers and risks in fire extinguishment operations, technological innovations can be utilized to assist firefighting.

This project focuses on the design and development of an autonomous firefighting robot capable of detecting, navigating, and extinguishing fires in hazardous environments. The robot will be equipped with a combination of thermal imaging, smoke sensors, and environmental mapping tools to effectively locate fires and operate in complex, obstacle-filled settings.

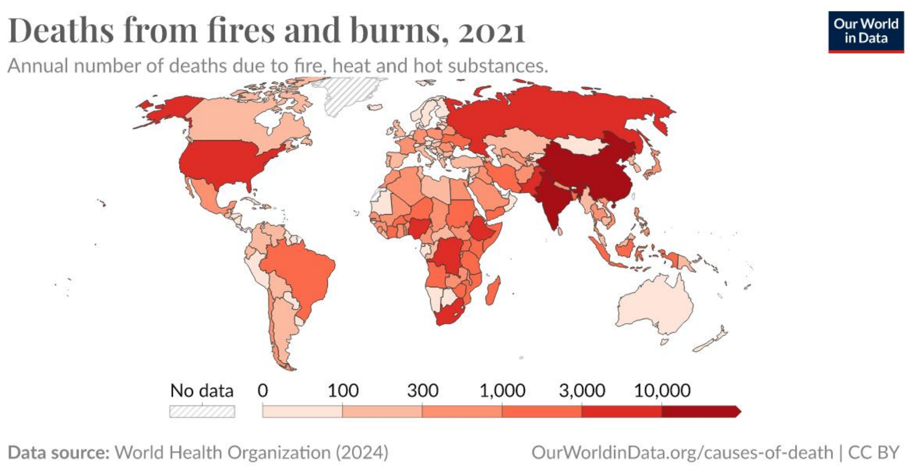
In this project, a firefighting robot is proposed which detects and extinguishes fire with minimum human assistance. The proposed robot is designed to be able to work on its own or be controlled remotely. Using such robots, fire detection and rescue operations can be carried out with greater security and without putting firefighters in risky situations. The proposed firefighting robots have been developed for both autonomous and manual modes. This project highlights the integration of autonomous systems in emergency response scenarios, offering a reliable and scalable solution for real-world firefighting applications.

INTRODUCTION

The 3rd industrial revolution, also known as the digital revolution, led to the development of digital electronics that revolutionized computing and communication. While machines have remained in use for a long time, the ability to program them would prove to be revolutionary in the field of automation. Industry 4.0 comes with even better technologies like AI, Additive Manufacturing, IoT and Big data. These innovations reduce or even eliminate the need for human intervention since the data collected from the sensors is used to drive decision making in real time.

The question arises that what, in fact, is the scope of automation? Is it so that robots are going to replace humans in all activities? The question can be answered depending on the activity's relevance to 3D's of robotics, that are the Dull, Dirty and Dangerous. Dull tasks are repetitive and tedious. Dirty tasks are those which are unclean and hazardous like waste management and sewer inspection. Dangerous tasks are those which pose a high degree of risk to human life like firefighting and handling toxic substances like nuclear waste.

Quantifying the global impact of fires is a complex task. According to the World Fire Statistics report by the International Association of Fire and Rescue Services, there were 4.5 million fires and 30,800 deaths in countries with a combined population of 2.7 billion in 2018. This translates to 1.7 fires per 1,000 inhabitants and 1.1 deaths per 100,000 inhabitants that year. Being a high-risk activity, using robots to extinguish fires alongside humans can reduce human fatality and improve the handling of the situation, especially in areas that are not accessible to humans easily.



Annual number of deaths due to fire in year 2021

LITERATURE REVIEW AND EXISTING STUDIES

There have been many recent advances in the field of firefighting. Here are a few notable ones.

1. **Robotic Systems 3 (RS3)** : Los Angeles fire department has introduced RS3, a remote-controlled hose equipped vehicle which can pump out 2500 gallons of water or foam per minute. It's design included tracks instead of wheels that mitigate the use of rubber tyres. This has proved effective in a textile warehouse fire in 2020.

2. **Recent advancements include the use of drone swarms for forest firefighting**. These drones can perform tasks such as surveillance, mapping, and monitoring, enhancing the efficiency and safety of firefighting operations. But these drones can only do so much by monitoring and in real fire containing operation, requires a UGV (Unmanned Ground Vehicle) to assist it extinguish the fire. This paper broadly categorizes use of robotic systems in prevention, surveillance and disaster response.

3. **Protection of electronic equipment from heat** is an important challenge. In systems exposed to high temperatures, advanced cooling systems, heat pipes with phase change materials, ceramics, high temperature alloys, aerogels etc. Are effective in protecting electronics at high temperatures. The cruciality of this study in our project pertains to the fact that studies attribute 55% of electronic device failures to temperature.

Technology-Driven Innovations:

1) **Thermal Imaging Cameras:** These devices help firefighters see through smoke and locate hotspots, improving situational awareness and enhancing search and rescue operations.

2) **Augmented Reality (AR) and Virtual Reality (VR):** AR can overlay information onto a firefighter's view, providing real-time data on fire conditions and building layouts. VR is used for training, simulating realistic fire scenarios to improve response times and decision-making.

3) **Smart Helmets:** Equipped with sensors, cameras, and communication systems, these helmets provide firefighters with vital information and enhance safety.

Improved Techniques and Strategies:

1) **High-Pressure Water Mist Systems:** These systems use fine water droplets to suppress fires more effectively while minimizing water damage and reducing the risk of slips and falls.
2) **Predictive Analytics:** By analyzing data from sensors and historical records, firefighters can identify potential fire hazards and take preventative measures.
3) **Collaborative Robotics:** Human-robot collaboration is becoming more common, with robots assisting firefighters in tasks like hose handling and equipment transportation

PROBLEM FORMULATION:

Problem Definition.

The problem addressed in the project is the increasing severity of fires in various environments, which pose significant risks and challenges to human firefighters. The proposed solution is a firefighting robot based on the Raspberry pi platform, designed to navigate manually/autonomously, detect fires, and extinguish them using a water pump. The robot can be remotely controlled, reducing the risks faced by human firefighters. The proposed robot is intended to be efficient, effective, safe, and feasible, providing a valuable tool for firefighters to combat fires in various environments.

Objectives

- Fire Detection: To Implement a robust fire detection system using a combination of sensors and image processing techniques.
- Autonomous Navigation: Enable the robot to navigate autonomously, avoiding obstacles and reaching the fire source.
- Fire Suppression: Develop an effective mechanism to extinguish fire, such as a water pump or extinguisher.
- Real-time Monitoring: Provide real-time monitoring and control capabilities through a user-friendly interface.

ADVANTAGES OF FIREFIGHTING BOT

1. **Accessibility:** There are areas that may be affected by the fire but are inaccessible to human beings. Such as:
2. **Industrial sites:** In industrial sites, robots can navigate through hazardous environments like petrochemical plants where flammable materials pose a risk to humans.
3. **Collapsed structures:** Collapsed structures due to earthquakes and explosions may not be accessible to humans
4. **Forests and remote areas such as mountains:** In the summer of 2024, Himachal Pradesh saw spike in forest fires. But being a mountainous territory, it was inaccessible to conventional fire brigade. These fires are on the rise as global warming continues. In such places, firefighting bots can be air dropped to curtail the spread of wildfires.
5. **Gas filled environment:** Robots can be used in an environment where gases are toxic to skin and respiratory system.
6. **Situation monitor:** If the bot can be equipped with relevant sensors, it can be used to monitor the situation in real time.
7. **Autonomous real time decision making**
8. **Rescue operations:** An autonomous system can be of invaluable use when required to rescue the people in danger by leading them by the safe passages, preventing the fire from burning them and sending SOS signals to the brigade using location tracker for ease of operation.

OUR OBJECTIVE

We are working to design and fabricate a **UGV(Unmanned Ground Vehicle)** that extinguishes fire. As we know, this technology is in development by teams like THERMITE and Shark Robotics. There are a few issues with their models that we would attempt to tackle:

I. **Size complexity:** The models that are being developed by these companies are of large size. Large size offers good recoil capacity (when launching water through cannon), space to ensure longevity of electronic components, greater capacity of liquid or gas used in the operation, sustenance of impact during structure collapse etc. But size prevents the bot from being employed on real time monitoring conditions in sensitive locations. It also prevents the bot from entering areas inaccessible to humans due to size issue. Large size vehicles are obsolete when the fire is on the upper floors which would require it to climb the stairs. Heavy weight vehicles can cause structures to collapse.

II. **Complexity:** The complexity of existing systems is a major hinderance to the cost effectiveness of the solution. Thermite RS3 costs $278,000, this is comparable to the price of conventional fire trucks. We are trying to make the system as simple as possible using a SCB, sensors, cameras and water cannon. This kind of system would be affordable not just to the fire departments but also to residential complexes. It would be effective in preventing fires by real time monitoring and curtailing fires in their initial stages.

III. **Lack of fire detection capabilities:** These robots can be improved by fire detection capabilities which can help the user to target and extinguish fire. Our scope of development goes only till fire detection. But further development can make the system autonomously detect fire and extinguish it without human intervention.

IV. **Location tracking and guiding the trapped persons:** A system with computer vision can be used to find trapped persons and guide them through safe passages to escape, this can be done with a human operator handling the remote interface. Moreover, the bot can prevent the persons from having burns. Since Raspberry pi is capable of GPS, the bot can help the fire brigade rescue the persons thus reducing the fatalities.

The bot that is going to be developed by us is going to be programmed using a Raspberry pi 3 and consists of a camera and important sensors like smoke detection sensor. The CV library of python can be used to make heat map that will help in detection of fire.

Since it is a prototype, the robot is designed to be controlled using Bluetooth remote. In case of autonomous systems, this human user interface can be eliminated. It can also be tracked using

GPS. The extinguisher that is used is water because handling CO2 is a hazardous task, especially in the initial stages of development. The bot is propelled by a track mechanism that will eliminate the need of tyres that can melt in high temperatures. The water can be accessed using two methods, first is to connect the pipeline to the robot and the second is to place prefilled tanks on the bot. The former gives the bot access to a larger pool of extinguisher while the latter gives the bot freedom to move without limitations due to pipe. For this model, we have chosen the latter approach. The water cannon works using a pump and two servo motors that can guide it's target

Given electronic equipment, the outer casing of our bot is going to be thermal resistant and handle high temperatures. In this model this forms the biggest challenge, development of a casing that can prevent heat penetration at a low cost.

METHODOLOGY AND STATUS

A firefighter bot consists of these crucial components:

- Raspberry Pi 5 with 64GB SD card for the program
- Temperature sensor
- Smoke detector
- 5MP camera
- Chassis
- Track for the wheels
- DC motors to propel the bot
- Thermal resistant coating made of either ceramic or high temperature alloys
- Power source
- Pump for water cannon
- Servo motors to set the target

MICROPROCESSOR PROGRAMMING

For this project the **Single Board Computer (SBC)** being used in Raspberry pi 5. Raspberry pi runs on linux based systems like Raspberry pi OS. It integrates the CPU, GPU, RAM, and other components onto a single board. The microcomputer supports Wi-Fi, Ethernet, and USB-connected devices like keyboards, mice, storage devices, webcams, and more.

The reasons for choosing Raspberry pi:

- **Cost effective**: While Raspberry pi is far costlier than Arduino or ESP32, the latter are totally different from the former given their limited abilities. Arduino and ESP32 are used for robotics where processing power requirement is less and commands are simple. Whereas Raspberry Pi supports a number of programming languages, has high storage capacity and it's processing power is enough to support multi tasking. By the standards of high end robotics applications, Raspberry Pi offers numerous benefits at minimum cost

- **Fire detection and monitoring using computer vision:** For fire detection and also monitoring, the bot will use computer vision. As a result it is a requirement for the bot's CPU to support computer vision and process a myriad of data simultaneously. Arduino's can only execute one command at a time. Moreover Raspberry Pi can be connected to a display and used with a graphical user interface (GUI). This makes it ideal for projects that require real-time video processing, desktop-like applications, or visual interaction, which Arduino can't provide as it lacks the ability to run a GUI.

- **Connectivity**: Raspberry Pi comes with built-in support for internet connectivity (Wi-Fi and Ethernet), making it more suitable for projects requiring network communication, web servers, or IoT (Internet of Things) applications. Arduino usually needs additional modules or shields to connect to the internet.

At the present moment, none of the team members have ever worked on a project that encompasses the use of Raspberry pi. As a result we have taken the time to understand the working of Raspberry pi in detail. As of now we are comfortable with basic level understanding of formatting the Raspberry Pi and running basic commands like LED's. We will procure our own SCB by October and try to integrate the CV (Computer Vision) into it. The program will include fire detection and targeting.

Code for initiating computer vision:

```
sudo apt-get update
sudo apt-get upgrade
sudo apt-get install python3-opencv
```

```
import cv2

see_face = cv2.CascadeClassifier(cv2.data.haarcascades + 'haarcascade_frontalface_default.xml')

capture = cv2.VideoCapture(0)

if not capture.isOpened():
    print("Camera not accessible")
    exit()

while True:
    ret, frame = capture.read()
    if ret:
        gray = cv2.cvtColor(frame, cv2.COLOR_BGR2GRAY)
        faces = see_face.detectMultiScale(gray, scaleFactor=1.1, minNeighbors=5, minSize=(30, 30))
        for (x, y, w, h) in faces:
            cv2.rectangle(frame, (x, y), (x+w, y+h), (255, 0, 0), 2)
        cv2.imshow('Face Detection', frame)
        if cv2.waitKey(1) & 0xFF == ord('q'):
            break
    else:
        print("Failed to grab frame")
capture.release()
cv2.destroyAllWindows()
```

The code inspired from introductory blog on geeks for geeks website.

DESIGN

Design Methodology for the Development of a Firefighting Robot:

1. Problem Identification and Requirements Analysis

The initial step in the design process involved identifying the core problem the firefighting robot needed to address. This primarily focused on the challenges associated with fire hazards in environments that are difficult or dangerous for human firefighters to access.

Key requirements were determined based on:

The need for fire detection in real-time, using sensors capable of identifying heat sources and smoke.

Mobility in unpredictable and obstacle-filled environments, such as industrial or residential buildings.

Durability to withstand high temperatures, smoke, and moisture.

The robot's ability to extinguish the fire either autonomously or remotely under human supervision, depending on the complexity of the scenario.

2. Conceptual Design

Locomotion: Different movement mechanisms were evaluated, including wheeled and tracked options. Initially wheels are chosen for the robot as they provide better stability and are more energy efficient than in tracked due to less friction

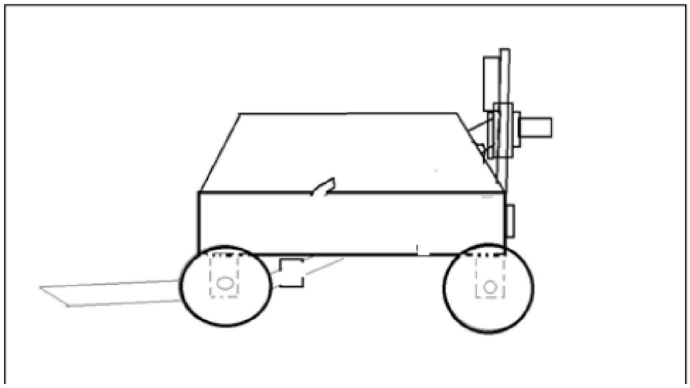
Extinguishing System: Various firefighting methods such as water, foam, or chemical extinguishers were assessed. The chosen system depended on the robot's expected operational environment, with water-based suppression emerging as the most versatile option for general use.

Sensor Suite: Sensors were selected to detect fire and navigate the robot. This included a combination of thermal cameras for heat detection, smoke sensors for identifying fire presence, and ultrasonic or LiDAR sensors for environmental mapping and obstacle avoidance.

3. Detailed Design

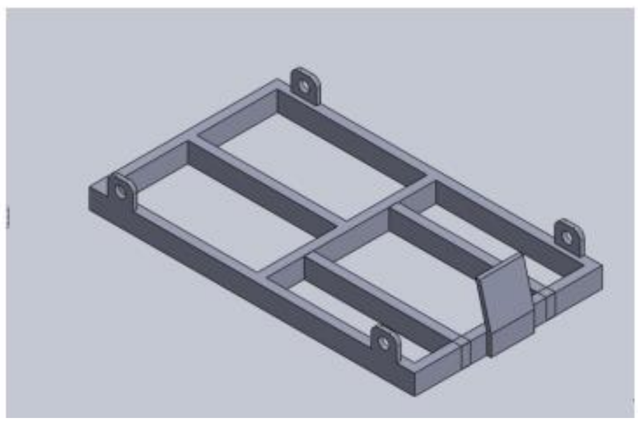
With a chosen concept, the detailed design will focus on developing the mechanical, electrical, and software systems in depth:

Mechanical Design: The body of the robot was designed using CAD software to create a chassis that could withstand harsh environments, support the robot's extinguishing system, and house its internal electronics. A heat-resistant outer casing will be added to protect sensitive components in the later stages of the development.

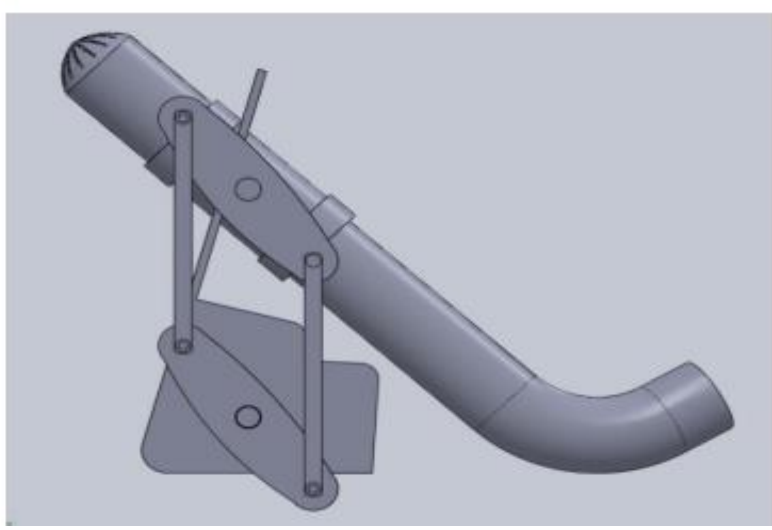


Schematic diagram of the model of the robot

The parts of the robot are shown with isometric and different side views:

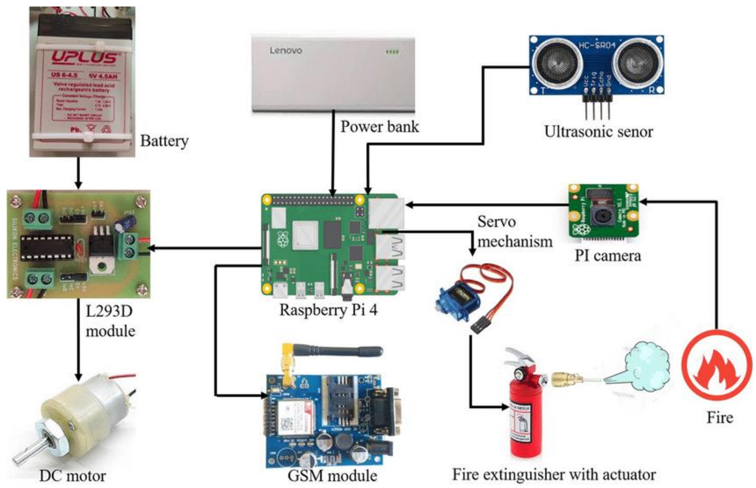


Model of the chassis of the fire fighter bot



Side view of the model of Nozzle control mechanism

For the main structure of the robot, to get the preferred movement and speed, we will be using two wheels at rear side and two wheels at front side. The wheels could stabilize the robot and rotate up to 360 degrees. The body of the robot will be made from acrylic polymers and metals to protect the electronic circuit. The acrylic sheet is resistant to heat of up to 200 ^{0} C.



MATERIAL

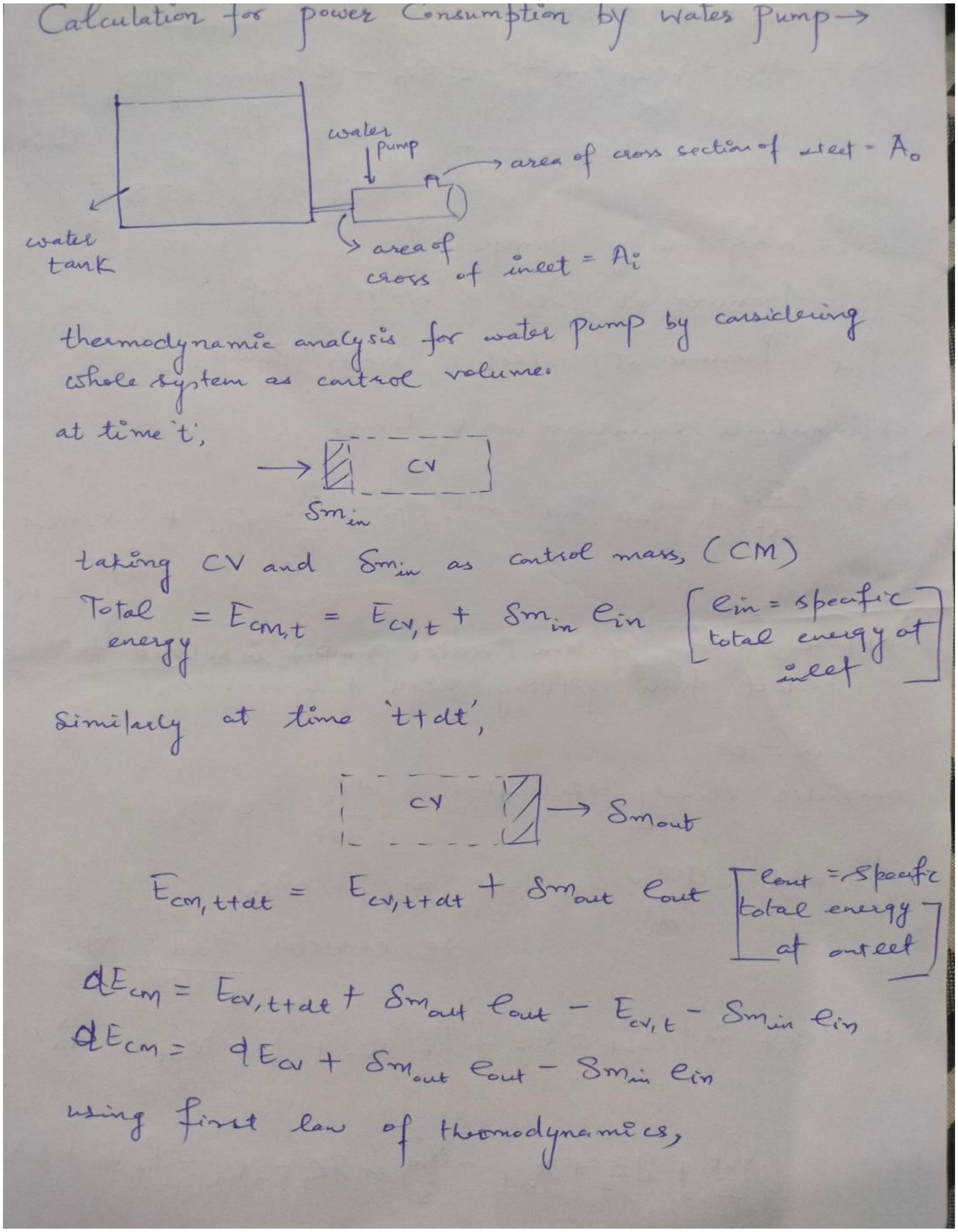
Based on our literature review we have found the following materials that can be used for insulating the electronic parts of the bot along with the water tank to prevent evaporation.

Material	Advantages
1. Al alloys	- Lightweight - Corrosion resistant (CR) - Good heat resistance - Cost-effective
2. Ceramics	- Outstanding heat resistance - Non-conductive
3. Phase change materials (Heat pipe)	- Very durable - Excellent CR - High temperature resistance

Heat-resistant Plastics:

Plastic	Heat Resistance	Applications
1. Polyimide	Up to 400°C	Excellent electrical insulation
2. Liquid crystal polymer	Upto 240°C	low thermal expansion
3. Polyphenylene sulfide	Up to 200°C	Used in automotive industry
4. Polyamide-imide	Up to 275°C	Used in aerospace industry

Calculations



Calculation for power Consumption by water pump→

thermodynamic analysis for water pump by considering whole system as control volume.

at time 't',

taking CV and δm_{in} as control mass, (CM)

$$\text{Total energy} = E_{cm,t} = E_{cv,t} + \delta m_{in} e_{in}$$

[e_{in} = specific total energy at inlet]

Similarly at time 't+dt',

$$E_{cm,t+dt} = E_{cv,t+dt} + \delta m_{out} e_{out}$$

[e_{out} = Specific total energy at outlet]

$$dE_{cm} = E_{cv,t+dt} + \delta m_{out} e_{out} - E_{cv,t} - \delta m_{in} e_{in}$$

$$dE_{cm} = dE_{cv} + \delta m_{out} e_{out} - \delta m_{in} e_{in}$$

using first law of thermodynamics,

Firstly, we have calculated (approximate) the power consumption by water pump using thermodynamic analysis for open system.we fixed volume(control volume) inside water pump and calculated the amount of work done by water pump.

We took some assumptions,

Like here we consider steady state then the mass flow rate become constant.

Also we consider water as an incompressible fluid.
The volume flow rate become constant as per two assumptions we mentioned above.
The rate of change of total energy of control volume =0 , as we consider steady state flow.

$$\delta Q = dE + \delta W$$

$$\delta Q = dE_{cv} + \delta m_{out} e_{out} - \delta m_{in} e_{in} - P_{in} \frac{\delta m_{in}}{\rho_{in}} + P_{out} \frac{\delta m_{out}}{\rho_{out}} - \delta W'$$

$\delta W'$ = Work done by pump.
P_{in} = Pressure at inlet of water pump.
P_{out} = Pressure at outlet of water Pump

differentiate equation w.r.t. time,

$$\dot{Q} = \frac{dE_{cv}}{dt} + \dot{m}_{out} e_{out} - \dot{m}_{in} e_{in} - \frac{P_{in}}{\rho_{in}} \cdot \dot{m}_{in} + \frac{P_{out}}{\rho_{out}} \cdot \dot{m}_{out} - \dot{W}'$$

Suppose whole system (water pump) insulated to protect from getting high temperature,

$$\dot{Q} = 0$$

consider steady state flow, $\frac{dE_{cv}}{dt} = 0$

and $\frac{dm_{cv}}{dt} = 0 \Rightarrow \dot{m}_{out} = \dot{m}_{in}$

so, consider $\underline{\dot{m}_{out} = \dot{m}}$

$$0 = 0 + \dot{m}\left[e_{out} - e_{in} - P_{in} v_{in} + P_{out} v_{out}\right] - \dot{W}'$$

$$\dot{W}' = \dot{m}\left[\frac{V_{out}^2}{2} + gz_2 + u_{out} - \frac{V_{in}^2}{2} - gz_1 - u_{in} - P_{in} v_{in} + P_{out} v_{out}\right]$$

Because the system (water pump here) is insulated so that it can be protected from high temperature, the Q = 0.
The specific internal energy at inlet and outlet is approximately same, this si our assumption because in real there can be some difference between them.
We have calculated velocities at inlet and outlet using formula, Q= v*A , where Q is volume flow

rate, v= velocity at inlet or outlet, A = area of ceoss section at inlet or outlet.

As system is at same level, $z_1 = z_2$

water is approximately incompressible hence, $v_{in} = v_{out}$

$v_{in} = v_{out}$ = specific volume = $\frac{1}{\rho_{water}}$

$$\dot{W}' = \dot{m}\left[\frac{V_{out}^2}{2} - \frac{V_{in}^2}{2} + u_{out} - u_{in} + P_{out}\, v - P_{in}\, v\right]$$

u_{out} = specific internal energy at outlet.

u_{in} = specific internal energy at inlet.

$$\dot{W}' = \rho Q\left[\frac{V_{out}^2}{2} - \frac{V_{in}^2}{2} + 0 + v\left[P_{out} - P_{in}\right]\right]$$

$\rho = \frac{\dot{m}}{Q}$ $Q \rightarrow$ flow rate and $u_{in} \approx u_{out}$ [Assumption]

$$\dot{W}' = \rho Q\left[\frac{V_{out}^2}{2} - \frac{V_{in}^2}{2} + v\left[P_{out} - P_{in}\right]\right]$$

Q = constant ⇒ because steady flow which implies constant mass flow rate and ρ is same everywhere [water is considered incompressible]

$Q = A_{out} \cdot v_{out}$ and $Q = A_{in} \cdot v_{in}$

$$\dot{W}' = \rho Q\left[\frac{Q^2}{2A_{out}^2} - \frac{Q^2}{2A_{in}^2} + v(\Delta P)\right] \text{ ——— } (*)$$

Here we mention that the power deleivered by water pump will not exactly same as power given by motor. So there will be some losses.so we took here eta as efficiency of water pump.
Similarly there will be some losses in motor so we took eta for motor also.hence the total effieciency of system become product of efficiencies of motor and water pump.In this way we calculated the power consumption by system through battery.we can then take battery accordingly.

Suppose the efficiency of water pump = η_{pump}

$$\text{Power required by pump} = \frac{\dot{W}'}{\eta_{pump}}$$

[$\dot{W}'$ can be calculated by putting values in equation *.]

[η_{pump} will be given with pump specification]

So, $\overset{1}{P}$ = power required by pump $= \frac{\dot{W}'}{\eta_{pump}}$

$\overset{1}{P}$ is the power output by motor used for pump.

Motors have efficiency = η_{motor}

$$\text{Power input to motor} = \frac{\overset{1}{P}}{\eta_{motor}}$$

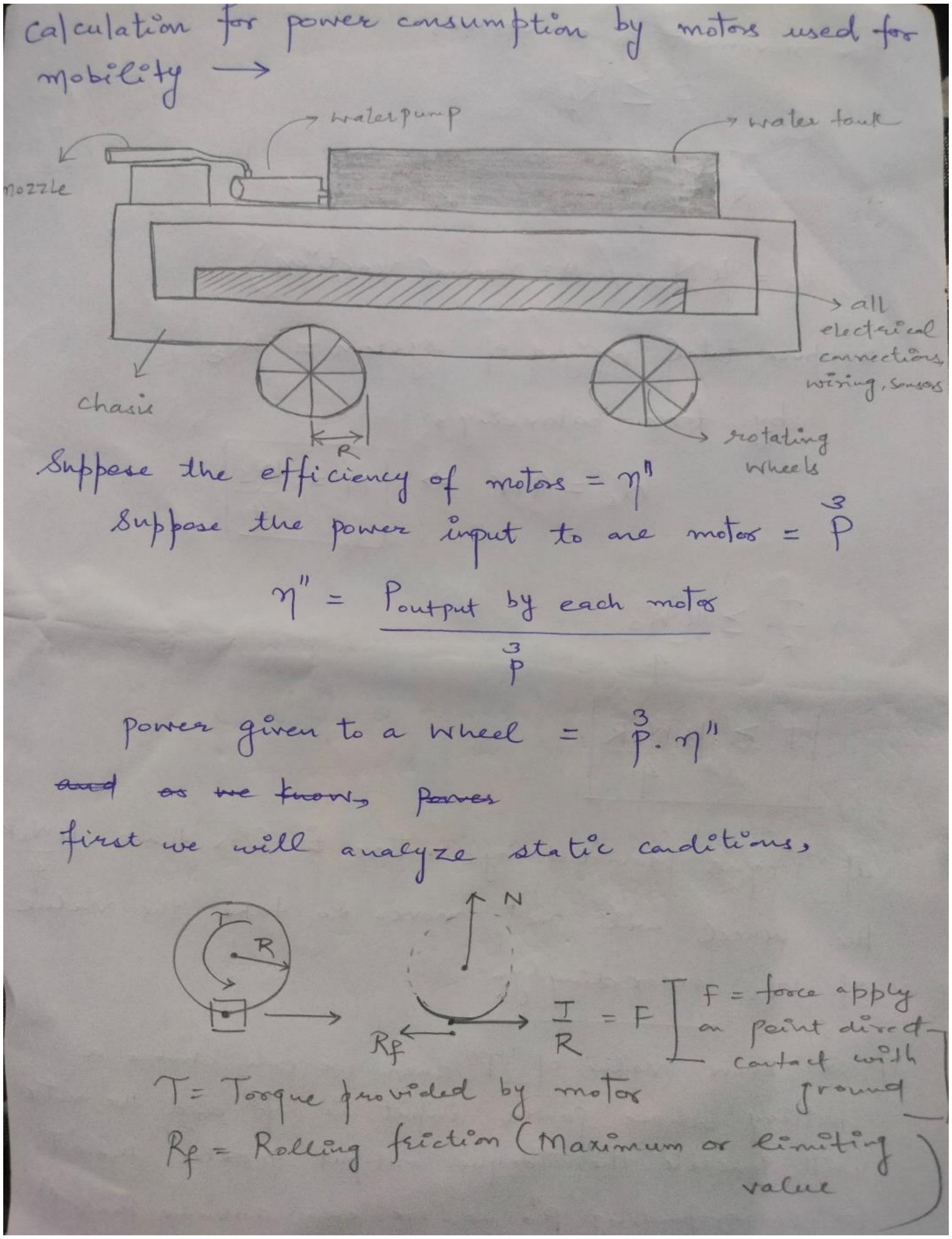
Power input to motor $= \overset{2}{P} =$ Power given by Battery

So, $\overset{2}{P} = V \times I$

Hence, $\frac{\overset{1}{P}}{\eta_{motor}} = V \times I$ [we know, $\overset{1}{P} = \frac{\dot{W}'}{\eta_{pump}}$]

So, $\frac{\dot{W}'}{\eta_{pump} \cdot \eta_{motor}} = V \times I \Rightarrow \boxed{VI = \frac{\dot{W}'}{\eta_p \cdot \eta_m}}$

In this section we calculated the minimum power required for movement of fire fighting robot.because here weight considerations are important because as the weight will increase the amount of static friction will also increase,so tial movement of system we have to choose a battery which provides the torque which can overcome the torque provided by friction.


Calculation for power consumption by motors used for mobility →

Suppose the efficiency of motors = η''

Suppose the power input to one motor = $\overset{3}{P}$

$$\eta'' = \frac{P_{output} \text{ by each motor}}{\overset{3}{P}}$$

power given to a wheel = $\overset{3}{P} \cdot \eta''$

~~and as we know, power~~

first we will analyze static conditions,

$$\frac{T}{R} = F$$ [F = force apply on point direct contact with ground]

T = Torque provided by motor

R_f = Rolling friction (Maximum or limiting value)

As we can see in image, we have calculated minimum torque which the motor should act on wheel to overcome frictional torque.

For movement to be occur,

$$F \geq R_f$$

$$\frac{T}{R} \geq R_f$$

$$R_f = \mu N \quad (N = \text{Normal reaction})$$

Suppose total weight of system $= W_S$

by force balancing,

$$W_s = 4N \Rightarrow \boxed{N = \frac{W_s}{4}}$$

$$\frac{T}{R} \geq \mu \frac{W_s}{4}$$

$$\boxed{T \geq \mu \frac{W_s R}{4}}$$

If Torque provided by motors is less than $\mu \frac{W_s R}{4}$ the wheel will not move. So take the value of W_s accordingly.

If we know value of 'T' then we can choose a battery whose power input is P'' and the motor will generate the Torque output greater than 'T' for corresponding P''. So, we can assume that P''

Here we consider the power consumption by microcontroller and other electrical components like resistors etc.also there should be some power consumed by other devices like LED's and sensore(if any).

By summing all the power consumed we get an approximate idea for total power consumed by whole system.but there can be some more calculations regarding control and dynamics of robot, which we will consider later.

is power input required to motor for generating Sufficient torque to overcome Rolling friction.

consider power consumption by microcontroller and all circuits components = P_{mc}

consider power consumption by ~~sensors used fo~~ other components (if any) = P_{others} (like power consumption by LED's)

Total power consumption = $\overset{2}{P} + 4P'' + P_{mc} + P_{others}$

$$\boxed{\sum P_{ower} = \overset{2}{P} + 4\overset{''}{P} + P_{mc} + P_{others}}$$

$\overset{2}{P}$ = power consumption by water pump.

$\overset{''}{P}$ = minimum power used by motors attached to wheels for just starting movement.

P_{mc} = Power consumed by microcontroller + all circuit other components

P_{others} = Power consumed by other components like LED's, sensors (if any) etc_.

$\boxed{\text{NOTE}}$ → we can do calculation for Robot under motion and its fire spraying mechanism also. (this part will be covered also)

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