PROJECT PROPOSAL FOR A SEARCH-AND-RESCUE SOCIAL ROBOTIC SYSTEM

PDE3413

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PDE3413 – Mobile Robot Proposal

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Contents

Abstract

I was approached to design a small to medium sized cost-effective social mobile robot to assist in search-and-rescue operations in urban areas. In this proposal I will explain the context of search-and-rescue operations — the conditions the robots must operate under, the necessary features to operate under those conditions and the capabilities provided by the robots to aid search-and-rescue operators.

I will describe several of the currently available solutions for rescue robots in four key categories: large, small, flexible, and aerial. Each can provide its own set of advantages and, as such, we will also explore how the proposed solution could be used alongside other types of rescue robots to improve rescue efforts while reducing the danger the rescue team are exposed to.

I will then describe how my proposed solution would work specifically, explaining the choices in sensors, processors, actuators, and motors and how all the parts in the system are connected and controlled.

Background research

Target audience

This product will be developed entirely for use by **public safety agencies**. As such, there is a unique set of priorities that must be considered. When developing a product for a public agency, cost and public perception are extremely important. As such, this project was developed with cost in mind, exploring how to make the product more cost-effective, both in production and maintenance, while also preferring parts that can benefit from economies of scale.

This cost-to-performance based approach would reduce overhead for public agencies, which would also be positive for the public, as this would not be perceived as a waste of resources.

Since the robots being proposed will not be involved in policing or law-enforcement, there is a lesser risk of suffering political backlash for concerns about the automation of policing or the possible use of excessive force [1] and, as such, these concerns will not be addressed past this section, although the use of visual data, an area that can also be prone to controversy, will be explored later.

Reason for developing this product

Search-and-rescue operations are an extremely high stakes endeavour – they carry very high risk both for victims and for the teams in charge of bringing them to safety. In many situations, ensuring the environment is safe (ensuring there are no gases, for example) can be a lengthy process and that delays the deployment of the rescue teams [2].

The robots presented in this proposal aim to empower the rescue teams with crucial sensor data, such as gas and smoke levels, heat readings and visual data that would enable them to begin deployment more safely and quickly. The robots also have functionality that allows them to explore the environment independently after their initial assessment, employing visual, audio and motion detection sensors to attempt to locate victims, thus increasing the speed at which the rescue teams can aid them.

These robots can work in smoky areas where humans would need heavy oxygen tanks [3] and employ Ultra-Wideband radiofrequency modules that allow for their location to be calculated to high precision though Time Distance of Arrival (TDOA), also known as multilateration [4] – as such, the robots can provide extremely important topographical through their location and sensor information, which enables the emergency crews to create plans of action in real-time based on reliable information, increasing the chances of success for these operations.

Proposed Solution:

As detailed in the preceding sections, the task of this robot is to provide key data to empower emergency crews in search-and-rescue operations, and to assist them during the rescue efforts with the two-fold goal of increasing the speed and predictability of operations while also reducing the risk of casualties for both civilians and rescue crews.

Since this project is being developed for governmental agencies, cost is paramount. Solutions of this type in search-and-rescue contexts have seen little investment due to the very large cost of the available solutions, in favour of cheaper solutions, such as drones [5]. As such, it is important that costs are kept at a manageable level while still providing a high quality, easy to service robot with replaceable components, so that they can be kept operational with little upkeep costs and without the need for large investments in training specialized engineers.

Below is a list of the components used for the prototype of the robot presented in this proposal.

Estimated cost – Parts

Component Name	**Component Price** (packs shown in brackets)	**Component Image**	**Source**
Atmega2560 Microcontroller	£13.99		Amazon.co.uk
Raspberry Pi 4 Model B	£43.50		thepihut.com
Raspberry Pi Camera Module V2.1	£24		thepihut.com

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HC-12 Wireless serial communication module	£7.99		Amazon.co.uk
MQ2 Gas Sensor (Methane, Butane, Smoke)	£4.99 (1 unit) £ 2.05 / unit (5 units)		Amazon.co.uk
MQ5 Gas Sensor (Natural Gas, LPG)	£4 / unit (2 units)		Amazon.co.uk
LM35 Temperature sensor x5	£1.35 / unit (5 units)		Amazon.co.uk
HC-SR04 Ultrasonic sensors x2	£1.8 / unit (8 units)		Amazon.co.uk
HC-SR501 PIR Body Motion detector module	£1.8 / unit (5 units)		Amazon.co.uk
DWM1000 UWB 2-way range location module	£18.99 / unit (25+ units)		enrgtech.co.uk

DC Gear 12V Motor x4	£11.99 / unit		Amazon.co.uk
6DOF Robot Arm with MG996r servos x2	£59.99 / unit		Amazon.co.uk
PCA9885 PWM Servo Driver	£12.99		Amazon.co.uk
Dual TB9051FTG Motor Driver x2	£21 / unit		Pololu.com
REC14-12 12v 14Ah Battery	£41.99		Amazon.co.uk
MAX4466 Electret Microphone Amplifier	£2.66 / unit (3 units)		Amazon.co.uk
Mini USB Speaker	£10.90		thepihut.com

12v to 5v Power Converter	£6.99		Amazon.co.uk

Table 1 Component prices

The total price for components in the consumer market would be **£415.96**, but some costs might possibly be reduced by bulk orders and through direct orders.

However, the robot would be built with a 6061-aluminium chassis frame, which will account for a considerable portion of its material costs - according to the data collected while searching for prices, the cost for the chassis and sheet plating for the robot would be roughly **£200** before assembly. 6061 grade Aluminium is commonly used for chassis in the automotive industry as it provides a strong strength to weight balance. The reason for the need for a strong chassis will be explored in the design section.

This brings the total cost in materials to **£615.96**. Adding the cost for assembling the chassis and the rest of the robot, the total cost of the robot is estimated at **£1000 (+- £200).** This would still be highly competitive, as their compact size would reduce shipping costs and their simple maintenance, including the fact that components are easy to source and inexpensive, would mean they can be kept in working condition reliably without the need for highly trained engineers — all these factors (cost, maintenance, modularity, ease of transport) make this product a good fit for public agencies.

Power required and calculations

<table>
<tr><th><u>Component Name</u></th><th><u>Power factors</u></th></tr>
<tr><td>Mega 2560 Board</td><td>The processor will be powered by a 12v battery. As the board has voltage regulator, supplying its maximum recommended voltage of 12v will not result in adverse consequences. The board draws 50mA according to the specification.
<table>
<tr><td>Microcontroller</td><td>ATmega2560</td></tr>
<tr><td>Operating Voltage</td><td>5V</td></tr>
<tr><td>Input Voltage (recommended)</td><td>7-12V</td></tr>
<tr><td>Input Voltage (limits)</td><td>6-20V</td></tr>
<tr><td>Digital I/O Pins</td><td>54 (of which 14 provide PWM output)</td></tr>
<tr><td>Analog Input Pins</td><td>16</td></tr>
<tr><td>DC Current per I/O Pin</td><td>40 mA</td></tr>
<tr><td>DC Current for 3.3V Pin</td><td>50 mA</td></tr>
</table>
Although the documentation for the Mega board only rates the 3.3v pins at 50mA, this number does not apply to newer boards, in which the FTDI chip is replaced by a LP2985 regulator. This means the maximum current for recent boards, such as the one used for this project, is 150mA.</td></tr>
</table>

Raspberry Pi 4	The Raspberry Pi does not have a voltage regulator, and, as such, using 12v is not possible. For this reason, power will be supplied through a 12v to 5v converter with a micro-USB connection. The Pi4B uses between 500mA and 600mA while idling.
Raspberry Pi Camera	While not specified in the datasheet, the camera consumes 250mA while recording, according to research. It is connected to the Pi4B.
HC-12 Wireless serial communication device	This transmitter uses a power supply voltage of 3.2v to 5.5v. As such, it can be connected to the 3.3v pins in the Mega board. This device uses up to 100mA during transmission, which is within the 150mA current limit for the mega2560 3.3v pins.
MQ2 Gas Sensor	With a voltage of 5v and a heating consumption of less than 800w, the maximum current drawn by this sensor is 160mA.
MQ5 Gas Sensor	Same as above.
LM35 Temperature sensor x5	Can use between 5v and 30v. Can be connected to a 5v pin in the mega2560 board
HC-SR04 Ultrasonic sensors x2	Can be connected to a 5v pin in the mega board. **Working Voltage** — **DC 5 V** **Working Current** — **15mA**
HC-SR501 PIR Body Motion detector module	Can be connected to a 5v pin in the mega board. Voltage: 5V – 20V Power Consumption: 65mA
DWM1000 UWB 2-way range location module	Normal operation at 3.3v and current up to 160mA. Can be connected to mega board using a logic level shifter from 3.3v to 5v as 3.3v logic is not supported by default.
DC Gear 12V Motor x4	Connected to motor driver for 12v power. Rated current of 0.5A each, for a total of 2A.
6DOF Robot Arm with MG996 servos x2	Connect to PCA9885 servo controller. Each of the 6 MG996r servos for each arm operate on voltages of 4.8-7.2 and use a current of 500-900mA for a maximum total of up to 10.8A.
PCA9885 PWM Servo Driver	Connects to mega2560 board.
Dual TB9051FTG Motor Driver x2	Each connects to 12v supply, mega board and 2 motors.
MAX4466 Electret Microphone Amplifier	Uses 3.3v supply, connects to mega2560 board
Micro USB Speaker	This can be connected directly to the raspberry Pi

Table 2 Power calculations

The total maximum current used by the robot is **14260mA**. This is unlikely to be reached in normal operation, but still shows that a larger battery, such as 35Ah, might be necessary. Since this is likely extension, the robot is designed so that it can fit a battery of that capacity.

User Reviews – Reviews of parts

Component	User Reviews
Atmega2560 Microcontroller	ASIN: B06XKMZ3T9 Customer Reviews: 654 ratings, 4.7 out of 5 stars Best Sellers Rank: 4,422 in Computers & Accessories (See Top 100 in Computers & Accessories) 5 in Barebone PCs Date First Available: 31 Oct. 2016
Raspberry Pi 4 Model B	4.77 Based on 2,159 reviews
Raspberry Pi Camera Module V2.1	4.74 Based on 306 reviews
HC-12 Wireless serial communication module	ASIN: B01H2D2RH6 Customer Reviews: 186 ratings, 3.9 out of 5 stars Best Sellers Rank: 5 in GPS Traffic Message Channel Receiver Modules Date First Available: 14 Jun. 2016
MQ2 Gas Sensor (Methane, Butane, Smoke)	Customer reviews 4.5 out of 5 152 global ratings 5 star 65% 4 star 23% 3 star 8% 2 star 1% 1 star 3%
MQ5 Gas Sensor (Natural Gas, LPG)	Customer reviews 3.3 out of 5 4 global ratings 5 star 45% 4 star 0% 3 star 28% 2 star 0% 1 star 28%
LM35 Temperature sensor x5	ASIN: B00PCSP7MG Customer Reviews: 3 ratings, 4.7 out of 5 stars Best Sellers Rank: 56,545 in Business, Industry & Science (See Top 100 in Business, Industry & Science) 311 in Temperature Probes & Sensors Date First Available: 5 Feb. 2015

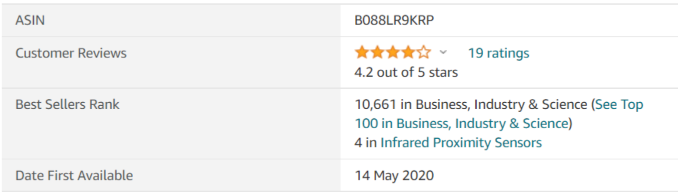
Ultrasonic sensors x2	
HC-SR501 PIR Body Motion detector module	
DC Gear 12V Motor	
6DOF Robot Arm with MG996r servos x2	
PCA9885 PWM Servo Driver	
REC14-12 12v 14Ah Battery	
MAX4466 Electret Microphone Amplifier	
Mini USB Speaker	

Table 3 User Reviews

As detailed in the above table, user reviews were analysed while selecting the components for the proposed robot, attempting to ensure a high degree of quality for an affordable price. Most of the components for the prototype are sourced from Business to Consumer (B2C) retailers, such as Amazon or The Pi Hut but, as the robot moves to production, industrial suppliers would more likely be contracted with providing the parts required – this would allow for better prices to be negotiated, possibly reducing the total cost by a significant amount, while also mitigating the effect of shortages or other supply chain issues on robot production.

Analysis of existing solutions

Mobile rescue, such as the one proposed in this document, are mostly deployed in two key activities in urban search and rescue operations – structural assessment and searching for victims. Robots employed in these tasks have traditionally worked as forward units, not side by side with the rescue teams [6].

However, social interaction with rescue robots may prove beneficial, and this is shown in scientific literature [6]. In the cited study, a remote-controlled robot with audio capabilities and visual sensors was placed in close contact with a rescue team. Shortly after, team members found that communicating through the robot was more practical and natural then using radios and even began using hand gestures towards the robot, as it effectively became a surrogate of the remote operator. When it was time to remove the robot, the team highly objected this, saying their efficiency would lower.

There has been enormous progress since 2004 in audio and visual processing techniques, which brings the idea developing a fully autonomous social rescue robot much closer to reality. Regardless, robots used in these contexts still tend to have no autonomy, being fully controlled by remote operators. In addition to this, mobile robots of the type being presented here tend to be extremely costly and, as such, they tend to be seen mostly in military applications.

In this section, I will describe some of the robots that provide similar functionality to the one proposed in this document, and others that, while not necessarily similar in design and functionality, work in the same context and that would, as such compete for the same areas.

This section will be divided in three areas according to their size in relation to our robot.

Large Robots

Shark Robotics Colossus

The Colossus, developed by Shark Robotics in France is a multi-purpose support robot developed in conjunction with Paris' Fire Brigade [7].

Figure 1 Colossus assisting in Notre Dame fire

This robot is fully remote-controlled and has highly powerful electric engines which allow it to reach a pulling capacity of one metric ton. It also boasts heat wave resistance up to 900C and up to 15 hours of autonomy, due to having six 27Ah lithium-ion batteries, bringing its total capacity to 162Ah.

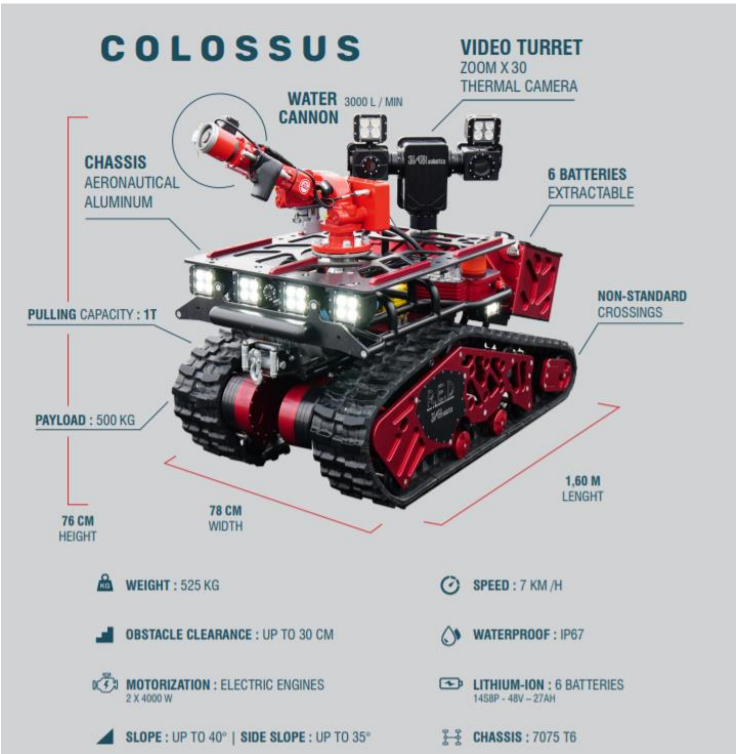


Figure 2 Colossus details

Although the Colossus is an extremely powerful robot, it weighs over 500 kilograms, and it moves quite slowly. As such, it is mostly used in direct support of fire brigades and rescue teams: extinguishing fires, carrying heavy loads, and assisting victims with modules for stretchers and breathing air systems.

It is also not equipped with any social capabilities for search and rescue situations.

Similar sized robots

Flir Packbot 510

The Packbot 510, developed by Teledyne Flir in the United States of America, is a lightweight robot used for bomb disposal, surveillance, and reconnaissance in a military context [8].

Figure 3 PackBot 510

This robot focuses on portability, weighing 23.9kg without batteries.

It uses BB-2590 batteries which are also quite light and portable, weighing 1.4kg and providing up to 15Ah in 12v mode.

However, since this robot is employed in a military context, its price is close to $50,000 and even the batteries cost upward of $400.

The PackBot is also fully remote-operated, offering no social interaction or communication capabilities other than the ones used to relay its sensor data.
It is equipped with several sensors to detect hazardous materials, four cameras, with support for a fifth thermal image capable camera and its manipulator lifts up to 20 kg.

Small robots

Unified Modular Snake Robot

While the Unified Snake robot is not used in the field, it provides unique and promising functionality. These robots have hyper-redundant mechanisms to move by changing their internal shape as a snake would [9]. This allows them to navigate through difficult terrain and, since they have a very narrow cross-section, they are also travel through tight enclosures or climb tree or pipes.

Figure 4 Unified Snake climbing a tree

The extreme mobility these robots possess allow them to be deployed into search and rescue environments, accessing places that would otherwise not be reachable by humans or other machines.

Proposal

Task at hand:

As seen in the solutions described above, social interaction or surrogacy are not often a priority in developing robots to be used in the context of search and rescue or even reconnaissance operations – as these robots are often used in military contexts, the use for such functionality may not be exist. However, a clear gap exists in the market when it comes to urban search and rescue robots for use in non-military contexts, where social capabilities would bring improve efficiency of rescue teams and reassure victims.

Proposed solution:

In this document I am proposing a search and rescue robot built with communication as a priority, providing a two-way channel between team leaders and their teams, but also between the rescue team and victims. These robots would work both in the frontlines, scouting the environment for hazards and mapping terrain, and alongside rescue teams, providing reassurance, hands-off communication channels and additional support.

The proposed robotic system will employ four DC motors for movement with two degrees of freedom, it will have two robotic arms, each with six degrees of freedom, to interact with and manipulate the environment and communication capabilities though its microphone and speakers.

The system will also employ several sensors: ultrasonic sensors are used to prevent the robot from falling at height, temperature and gas sensors assess the environment for safety, a camera is used to map the surroundings and, alongside a PIR body motion detector, look for survivors. It will also employ a two-way Ultrawide band transceiver to enable accurate location in indoors settings through multilateration, allowing its position to be tracked to high degree of certainty in real-time.

This system is developed to be used in teams of at least three. They can function as extenders to increase the range of communications of other robots in the team and they can attach to each other to provide increased pulling force through linking them with the built-in tow hooks and synchronising their movement. This would enable the robots to carry small loads and assist in clearing rubble or carrying equipment after their initial survey of the environment is complete and the teams have been deployed.

Concept Behaviour

In this section I will describe the expected functionality of each of the used components as well as the 3D design of the prototype along with annotations explaining how the components would fit and behave.

Mega 2560 board – used to connect and control sensors and motors and transmit data.

Raspberry Pi 4 B – controls the camera and speaker, communicates with Mega 2560 board through serial communication.

12v Battery – powers the system.

Pi Camera – Visual sensor, provides video images which can be analysed to search for survivors or study structural integrity, among other functions.

PIR Motion Sensor – used to detect movement to locate victims in rescue operations.

Temperature sensor – gather temperature data which can be used to find safer routes, identify the origin of fires.

Ultrasonic sensor – used to measure distance during movement to prevent the robot from falling into places it cannot climb out of.

Gas and Smoke sensors – detect hazardous gases and conditions to aid in rescue effort.

Robotic Arms – allow the system to interact with the environment, handling equipment and rubble. Also allows the robot to elevate its position to link with other robots using the tow.

Electret Microphone – Allows humans to communicate through the robotic system, relaying information to command or to other rescue team members.

HC-12 Wireless serial communication module – transmits data between robots and to the control centre.

PCA9885 PWM Servo Driver – Controls the servos in the robotic arms.

Dual TB9051FTG Motor Driver x2 – Each control 2 of the 4 DC motors in the system.

USB speaker – Used to produce sound, whether as a communication device, reproducing the sound captured by other robots or in the central control, like a radio, or playing messages built-in to the robot to communicate with and reassure victims, such as informing them their position has been sent to the rescue team.

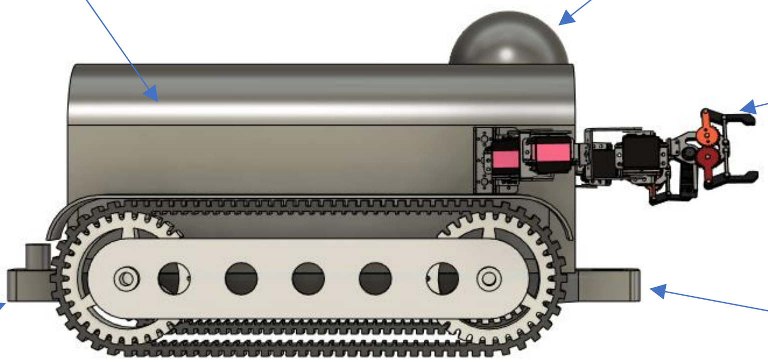


Figure 5 Robot mock-up profile

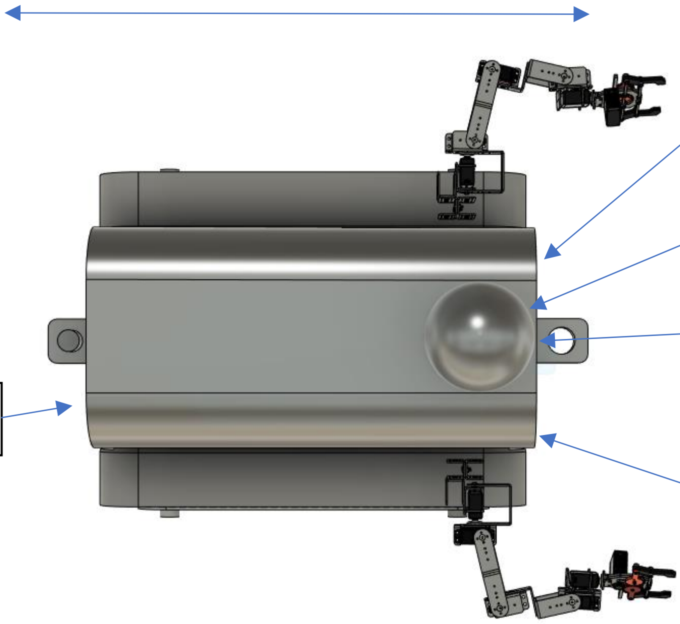


Figure 6 Robot mock-up top view

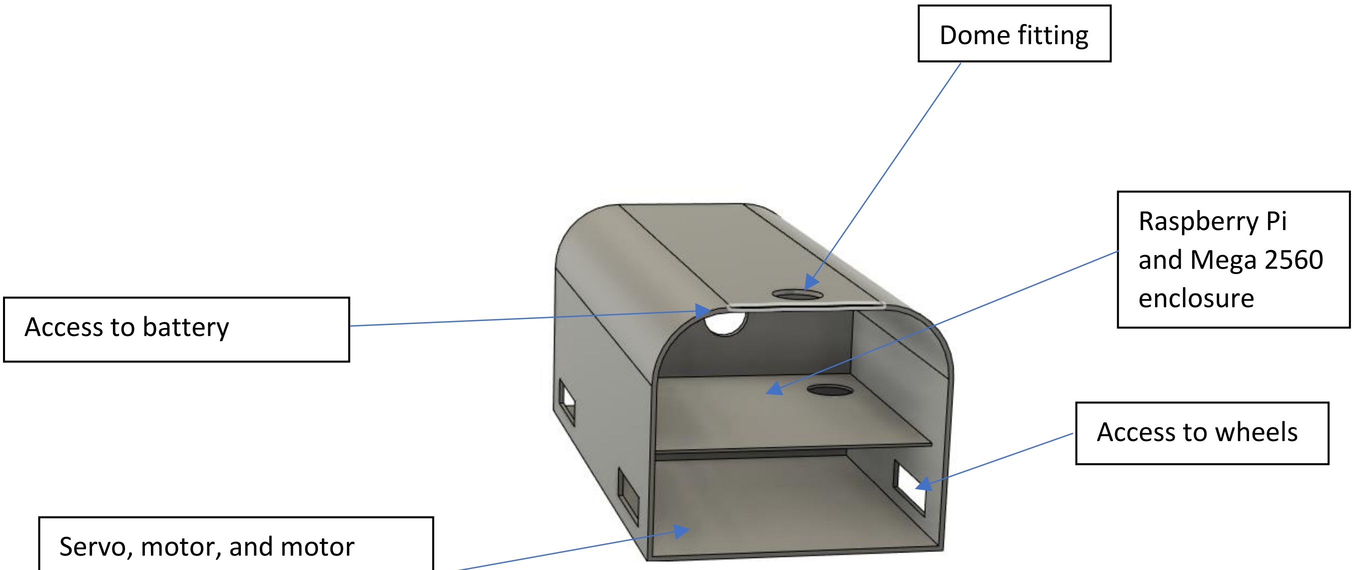


Figure 7 Robot mock-up empty shell front

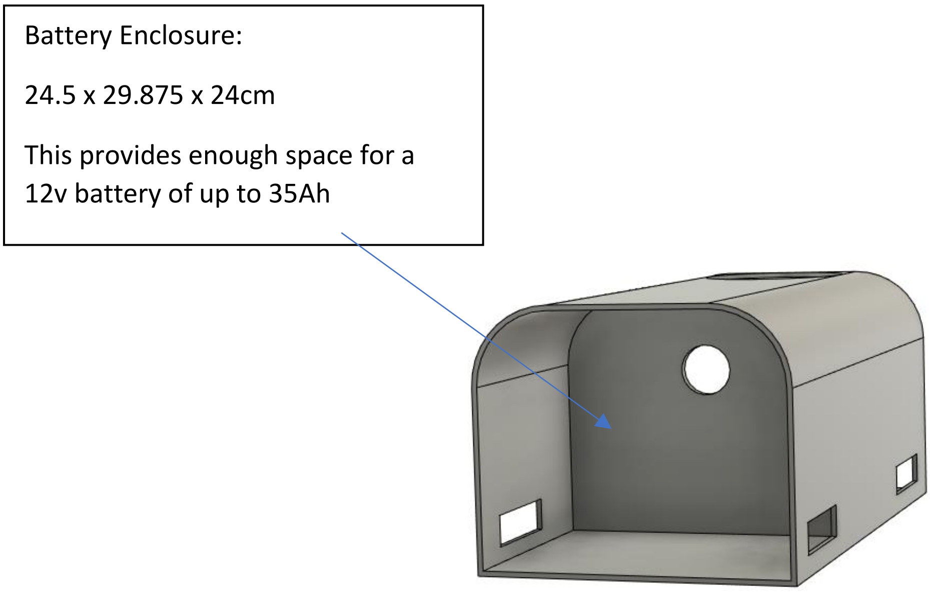


Figure 8 Robot mock-up empty shell back

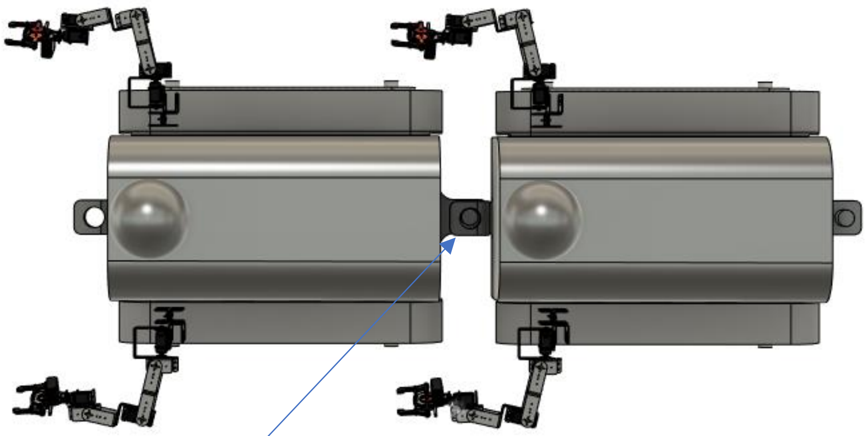


Figure 9 Top view of linked robots

Robots linking together to increase pulling power, allowing heavier loads to be carried.

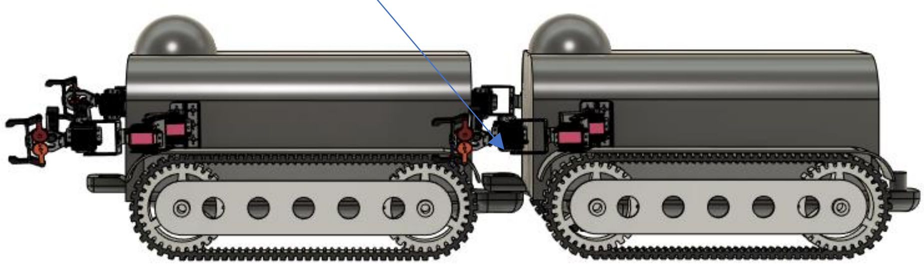


Figure 10 Profile view of linked robots

Functionality and Interaction with people and the environment

Environment reconnaissance

This robotic system is designed to be the first to enter an area at the start of a rescue operation. After being deployed by the rescue team, it can be remote controlled by an operative to access the area for hazardous conditions using its sensors.

It can detect smoke, gas, and high temperatures, while also providing a visual feed that can be used to plan the rescue team's strategy.

If it comes across victims during this initial phase, the operator can communicate directly with them using the system's microphone and speakers to provide instructions in real-time.

The robot's arms can also be used to interact with the environment, manipulating rubble, for example, to clear paths for itself, the rescue teams, or victims.

Locating Victims

After the rescue team has been deployed, the robots can be used to scout ahead or to look through harder to access areas, using the camera and motion detector to locate victims and to flag their location with a degree of precision using the 2-way ranging module. This module's high precision even in indoor settings would allow search efforts to be more focused, reducing the risk for all parties.

The operator can decide to maintain a conversation with the victim through the provided communication channels, calming them or providing instructions until help arrives.

The robot's arms can be used attempt to remove debris from the area around the victim.

Pulling loads

The robot can use its tow hook to pull loads such as equipment, emergency supplies, fire-retardant foil blankets, among other things. This functionality can be used to bring supplies to trapped victims if the robot can reach the area while the rescue teams are not able to.

Several robots can also link together – the system is designed so that its centre of mass is located closer to the rear which allows a robot to tilt itself slightly upwards using the actuators in the arms to push into the ground so that a second robot can drive in reverse to align its hook with the first robot's tow receiver.

In this context, the robots would effectively behave similarly to locomotives in double heading [10], coordinating their movements to double the resultant pulling force they are able to exert. This can be done using several robots, allowing heavy loads to be carried if there are no alternatives. It can also be used to attempt to pull heavy debris in hard to access areas to attempt to clear a passage.

Working alongside the rescue teams

Working side by side with the rescue teams, the robots would provide real-time tracking through their ranging module, allowing for each team's locations to be always known, while simultaneously offering communication channels, load carrying capabilities and sensors which can detect changes in the environment that had not been noticed up to that point. This ensures the teams can focus on the rescue operation while being safer and in having communication channels constantly available to them in a natural way, as they are able to speak to the robot as a surrogate of its remote operator.

Design

In this section I will describe the components used in robot and explain the reasoning behind my choices. I will also provide a system diagram showing how the components are connected.

Physical architecture

Processors:

- Raspberry Pi 4 B
- Mega 2560

Camera:

- Pi Camera v2.1

Sensors:

- MQ2 Gas Sensor
- MQ5 Gas Sensor
- LM35 Temperature Sensors
- HC-SR04 Ultrasonic Sensors
- HC-SR501 PIR Motion Detector
- MAX4466 Amplified Electret Microphone

Communication devices:

- HC-12 Wireless Transceiver
- DMW1000 2-way ranging module
- USB Speaker

Motors:

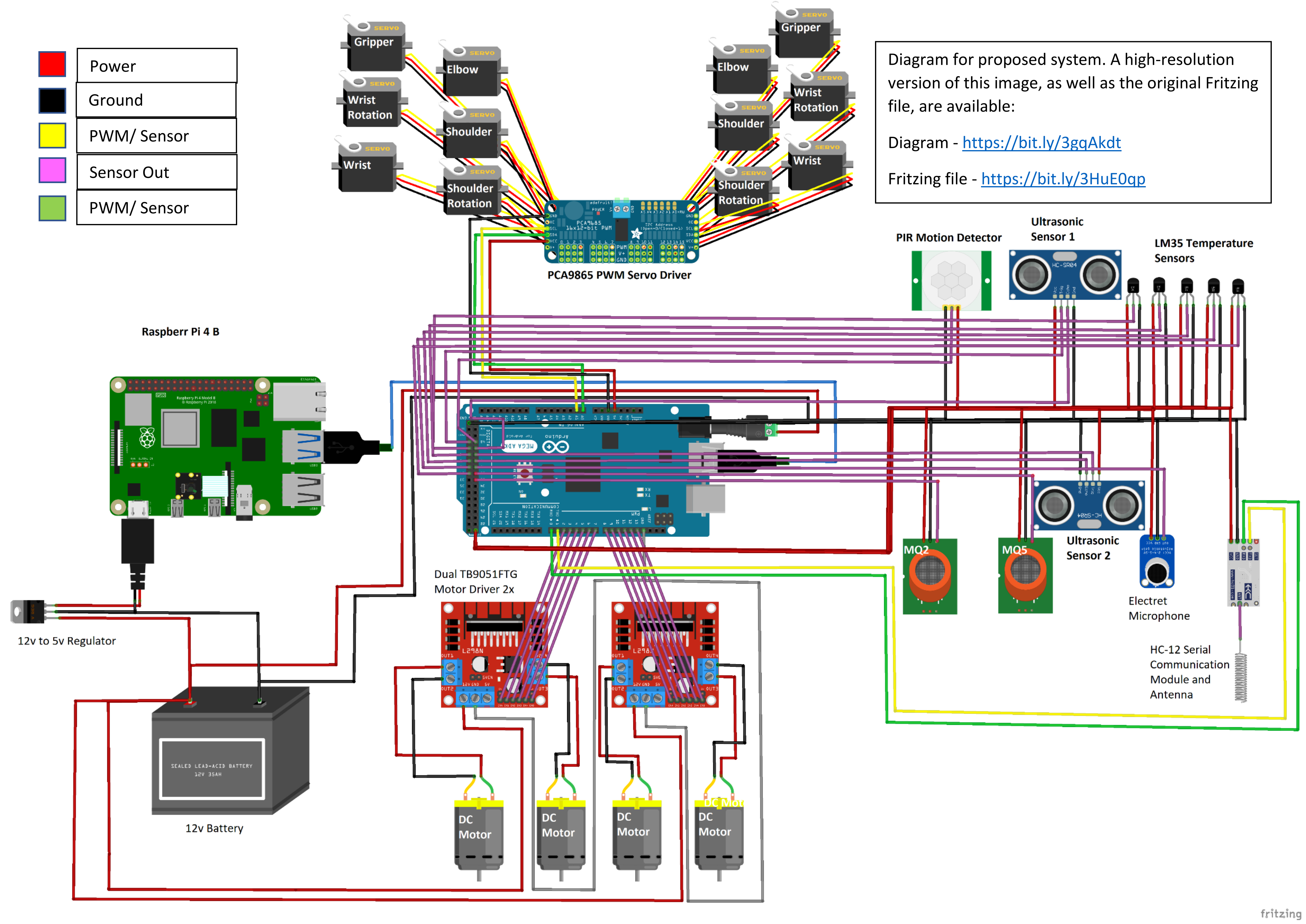
- 12v DC Gear motors
- Dual TB9051FTG Motor Driver

Actuators:

- MG996r 10Kg Torque Servo Motors
- PCA9885 PWM Servo Driver

Battery:

- REC14-12 12v 14Ah lead-acid Battery


Power
Ground
PWM/ Sensor
Sensor Out
PWM/ Sensor
Diagram for proposed system. A high-resolution version of this image, as well as the original Fritzing file, are available:
Diagram - https://bit.ly/3gqAkdt
Fritzing file - https://bit.ly/3HuE0qp
Gripper
Elbow
Wrist Rotation
Shoulder
Wrist
Shoulder Rotation
Gripper
Elbow
Wrist Rotation
Shoulder
Wrist
Shoulder Rotation
PCA9865 PWM Servo Driver
PIR Motion Detector
Ultrasonic Sensor 1
LM35 Temperature Sensors
Raspberr Pi 4 B
12v to 5v Regulator
Dual TB9051FTG Motor Driver 2x
MQ2
MQ5
Ultrasonic Sensor 2
Electret Microphone
HC-12 Serial Communication Module and Antenna
12v Battery
SEALED LEAD-ACID BATTERY 12V 35AH
DC Motor
DC Motor
DC Motor
DC Motor
fritzing

Sensors and sensor data

As specified above, the proposed system will employ several sensors to collect data from the environment. Their expected functionality and the data they are expected to collect is specified in this section:

Motion detection – PIR Motion Sensor – This sensor will be used to detect movement, which will aid in locating victims in rescue scenarios. Detecting motion will display an alert in the UI for the remote operator.

Gas sensors – MQ2 and MQ5 – These sensors detect smoke and hazardous gases. Upon detection of smoke or gas, the icon for the respective hazardous condition will light up in the UI so that the operator may act accordingly.

Ultrasonic Sensors – HC-SR04 – These sensors will be used to detect big differences in height on the floor by measuring the angle at which the signal bounces off the ground. This is done to prevent the robot from inadvertently falling at height and becoming stuck. They can also be used to avoid obstacles.

Temperature – LM35 – The LM35 sensors will be used to collect temperature data. An average of the value of all the sensors will be displayed at all times in the UI for the remote operator.

Voice - MX4466 Amplified Microphone – The microphone will capture audio data which will be run through a Speech to Text library for Python, such as the SpeechRecognition library [11], to provide logs and disambiguation. This will can be viewed in the UI for the system but will not always be displayed to avoid overwhelming the operator in chaotic situations. Audio will also be relayed to the operator through the system's wireless transceiver.

Video – Pi Camera V2.1 – The camera will be used to capture video data. This data will be relayed to the remote operator and will also be put through an OpenCV model in Python for human detection, such as the HOG model [12], highlighting humans in the UI. This will allow victims to be detected much quicker, speeding up the rescue effort.

Sensor Fusion

Sensor fusion would be done on the detections, not on the raw data [13]. As such mid-level sensor fusion would be employed to join the different data sources and produce a more complete model of the environment, applying Kalman filtering to the data [14].

Testing the system

Before being deployed to the field, the proposed robotic system will have to undergo a series of tests to ensure its functionality – these will be detailed below:

- Mega 2560 board
  - The board turns on and displays the "ON" led.
- Battery:
  - The battery's voltage is correct.
  - The battery's autonomy is within expected values.
- Raspberry Pi 4
  - The Raspberry Pi processor boots as expected.
- Pi camera
  - The camera can capture video
  - Human detection algorithm can successfully be applied to images captured by the camera.
  - Video data is displayed in the system UI.
  - Robot head can be rotated 180 degrees to each side to look at surroundings.
- Ultrasonic Sensors
  - The sensors detect the floor in normal operation and show an
  - The sensors can successfully flag increased differences in elevation, stopping the system from moving in the current direction.
- Temperature Sensors
  - The sensors successfully measure the temperature
  - The average measure of all sensors is calculated correctly and displayed in the system UI.
- Gas sensors:
  - Gas sensors do not detect gas in controlled setting with no gas.
  - Gas sensors detect smoke.
  - Gas sensors detect hazardous gases.
  - Gas detection information is successfully displayed in the system UI.
- Motion Sensor:
  - Sensor does not detect motion if no motion occurs.
  - Sensor detects motion if motion occurs.
  - Detection event displayed in system UI.
- HC-12 Transceiver:
  - Communication module can send data.
  - Commutation module can receive data.
  - Data transfer speed is above minimum threshold.
  - Data transfer maximum distance is above minimum threshold.
  - Data loss is below minimum threshold.
- MX4466 Microphone:
  - Microphone can capture audio data.
  - Audio data can be heard by remote operator.
  - Speech to text algorithms successfully applied to audio data.

- Robotic arm:
  - Servos can be controlled.
  - Each servo functions as expected.
  - System can successfully arms move with 6DOF.
  - System can lift load above minimum threshold.

Potential pitfalls

As it is right now, the prototype has flaws in some areas which can be improved upon in further iterations:

- Movement in stairs and rough terrain is not possible with the current wheel setup. This reduces the system's versatility in urban environments.
- Electret microphones introduce a great amount of noise and are overall low quality for speech purposes, which may negatively impact the system's communication.
- The current design of the robot is quite heavy, requiring more of the motor's power to carry out movement and leaving less force available for carrying equipment or assisting in rescue operations.

Future improvements

There are several improvements that can be made to the system to improve and expand its capabilities.

- Installing a higher quality camera with zoom capabilities and better performance in dark settings would allow for higher image quality.
- Installing a thermal imaging camera to aid in locating victims and mapping fires.
- Installing a larger battery to increase autonomy.
- Improving audio capture quality by installing multiple cardioid microphones, allowing for sound sources to be located with greater ease and improving communication capabilities.
- Improving the robot design to reduce costs in metal parts.

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