A Fully Autonomous 3D-Printed Search & Rescue Rover for Disaster Response

By

Abdulrahman Abougendia	22-101194
Fouad Hashesh	22-101062
Salah ElSayed	22-101188
Mohamed Farouk	22-101284
Jana Sherif	22-101234
Rokaya Radwan	22-101171
Habiba Ahmed	22-101143
Sara El-Dahshan	22-101226
Nour Hazem	23-101084
Amir Ashraf	23-101070

Faculty of engineering, Egypt University of informatics

May 2025

Table of Contents

Abstract

This project presents the design and implementation of a fully autonomous 3D-printed search and rescue (SAR) rover tailored for disaster response scenarios. The rover addresses critical challenges in conventional SAR missions, such as hazardous environments, limited visibility, and delayed victim detection, by integrating adaptive mobility, multi-modal sensing, and real-time communication.

Key innovations include:

- **Robust Mobility**: A 3D-printed PLA chassis and treaded wheels enable traversal of rough, debris-filled terrains, powered by NEMA17 stepper motors for precise control.
- **Multi-Sensor Fusion**: Thermal imaging (AMG8833), ultrasonic obstacle detection (SR04), and PIR motion sensing (SR501) synergize to locate survivors with high accuracy.
- **Autonomous Navigation**: A finite state machine (FSM) governs the rover's operation, combining obstacle avoidance algorithms with GPS (Neo-6M) and GSM (SIM800L) modules to relay victim coordinates to responders.
- **Power Efficiency**: Buck converters and LDO regulators optimize energy use, extending mission duration.

Test results confirm the rover's functionality in simulated disaster zones, demonstrating reliable victim detection, environmental adaptability, and real-time data transmission. While limitations in battery life and sensor resolution persist, the design offers a scalable, cost-effective foundation for future upgrades, including AI-driven navigation and modular payloads.

This project underscores the potential of autonomous robotics to enhance disaster response efficiency while minimizing risks to human rescuers.

Keywords: Search and rescue, autonomous rover, 3D printing.

2. Introduction

2.1 Background

Natural disasters, industrial accidents, and hostile environments (such as collapsed buildings or chemical spill zones) pose significant risks to human rescue teams. In these scenarios, time is critical, and the conditions may be too dangerous for direct human intervention. Search and rescue (SAR) robots have emerged as vital tools to locate survivors swiftly, assess hazards, and reduce responder exposure to danger. This project addresses the urgent need for an autonomous rover capable of navigating unpredictable terrains while reliably detecting victims and facilitating their extraction.

2.2 Problem Statement

Conventional SAR missions face challenges such as limited visibility, unstable structures, and hazardous materials, which delay rescue efforts and endanger responders. Many existing robotic solutions lack adaptability to diverse terrains or fail to integrate multi-modal detection systems for high accuracy. Our rover aims to overcome these limitations by combining robust mobility, advanced sensing technologies, and real-time communication to improve survival rates in disaster scenarios.

2.3 Objectives and Scope

The primary objectives of this project are:

- **Adaptive Mobility**: Design a rover capable of traversing rough, uneven, and debris-filled terrains (e.g., rubble, mud, or steep slopes).
- **Multi-Modal Target Identification**: Integrate sensors (thermal imaging, motion detection, and Ultrasonic traversal) to identify survivors with high accuracy.
- **Real-Time Communication**: Enable live data transmission to emergency authorities, including victim coordinates and environmental hazards via GPS and GSM modules.
- **Path Optimization**: Implement autonomous navigation algorithms to map and provide efficient extraction routes.

The scope focuses on prototyping a functional rover for simulated disaster environments, with scalability for real-world deployment.

3. Component Details

Electrical:

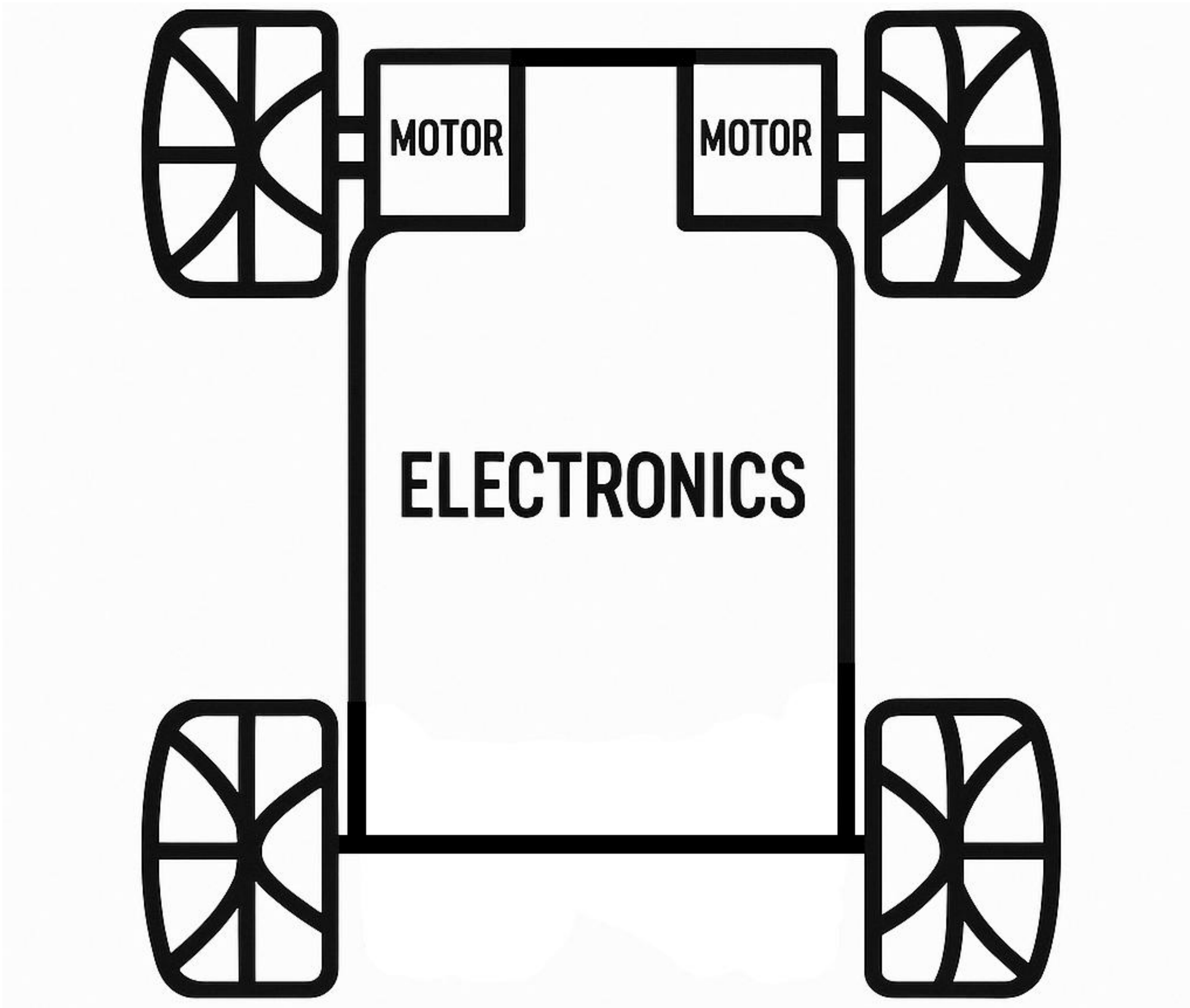
- LM2596S DC-DC Buck Converter 3A Step Down Module
- AMS1117 3.3V Power Module 800mA
- STM32F103C8T6 Microcontroller
- ESP32 Dev Module Microcontroller
- AMG8833 thermal camera
- SIM800L GSM Module
- Neo-6M GPS Module
- NEMA17 Stepper Motors
- A4988 Stepper motor drivers
- SG90 Servo motor
- SR04 Ultrasonic Sensor
- SR501 PIR motion sensor
- Diffused RGB Led
- Buzzer
- MPU-6050 IMU sensor (Gyroscope)

Mechanical:

- 3D printed PLA plastic wheels
- 3D printed PLA plastic Chassis (including top cover & bottom cover)
- m3 & m6 screws (mounting the motors and the Chassis covers)

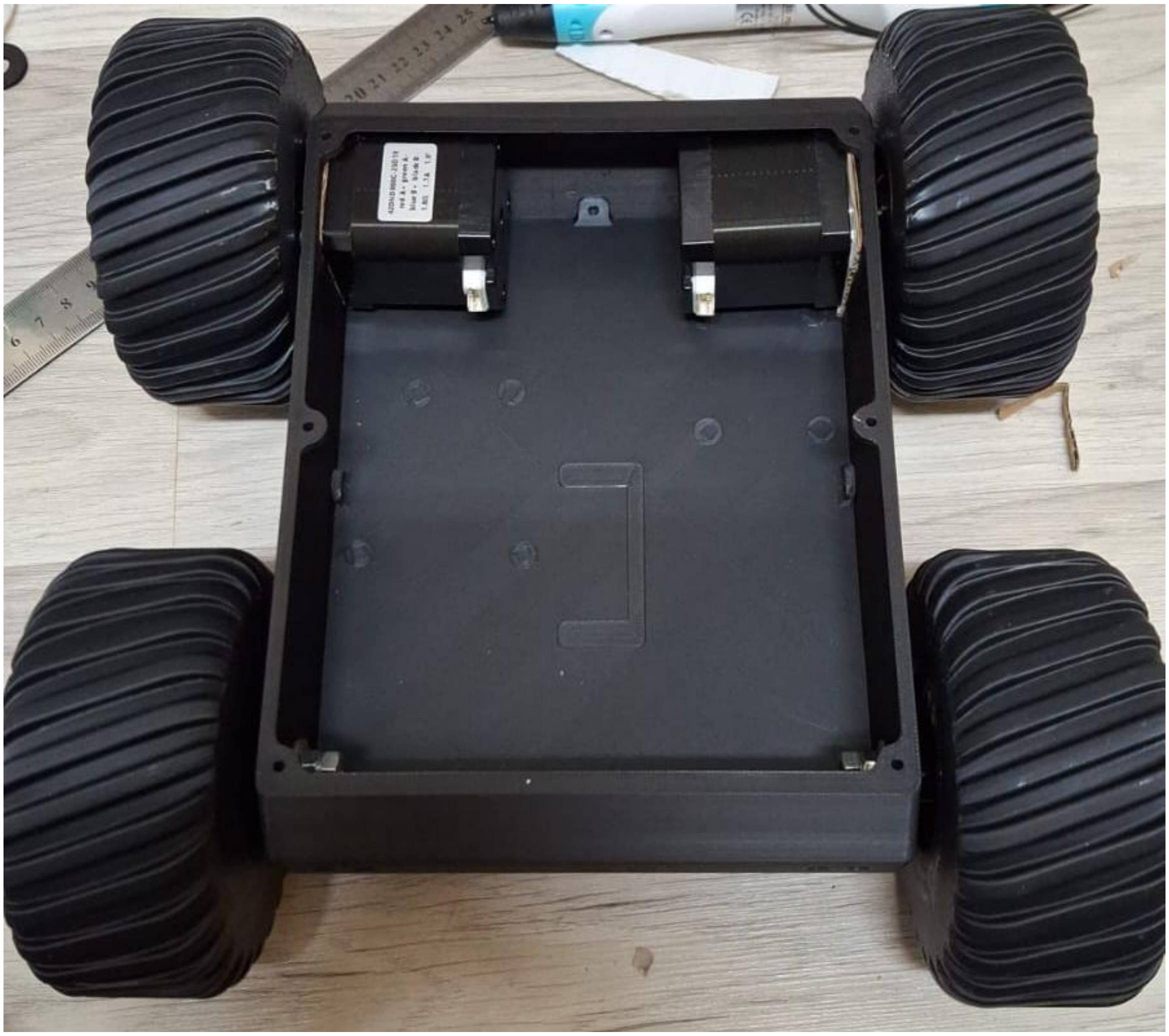
4. Design and Methodology

4.1 System Overview:



We approached the design concept in a simple manner by embedding electronics into a single bundle in the cavity of the mesh which shields electronics from dust/moisture while allowing passive cooling. However, we left some spots (like the one between the two motors) for components that need external outreach. Two motors in a pulling setting were found favorable over 4 motors because it reduces the number of complications that may arise during operation.

4.2 Mechanical Design



All parts were fully 3D printed with PLA filament including:

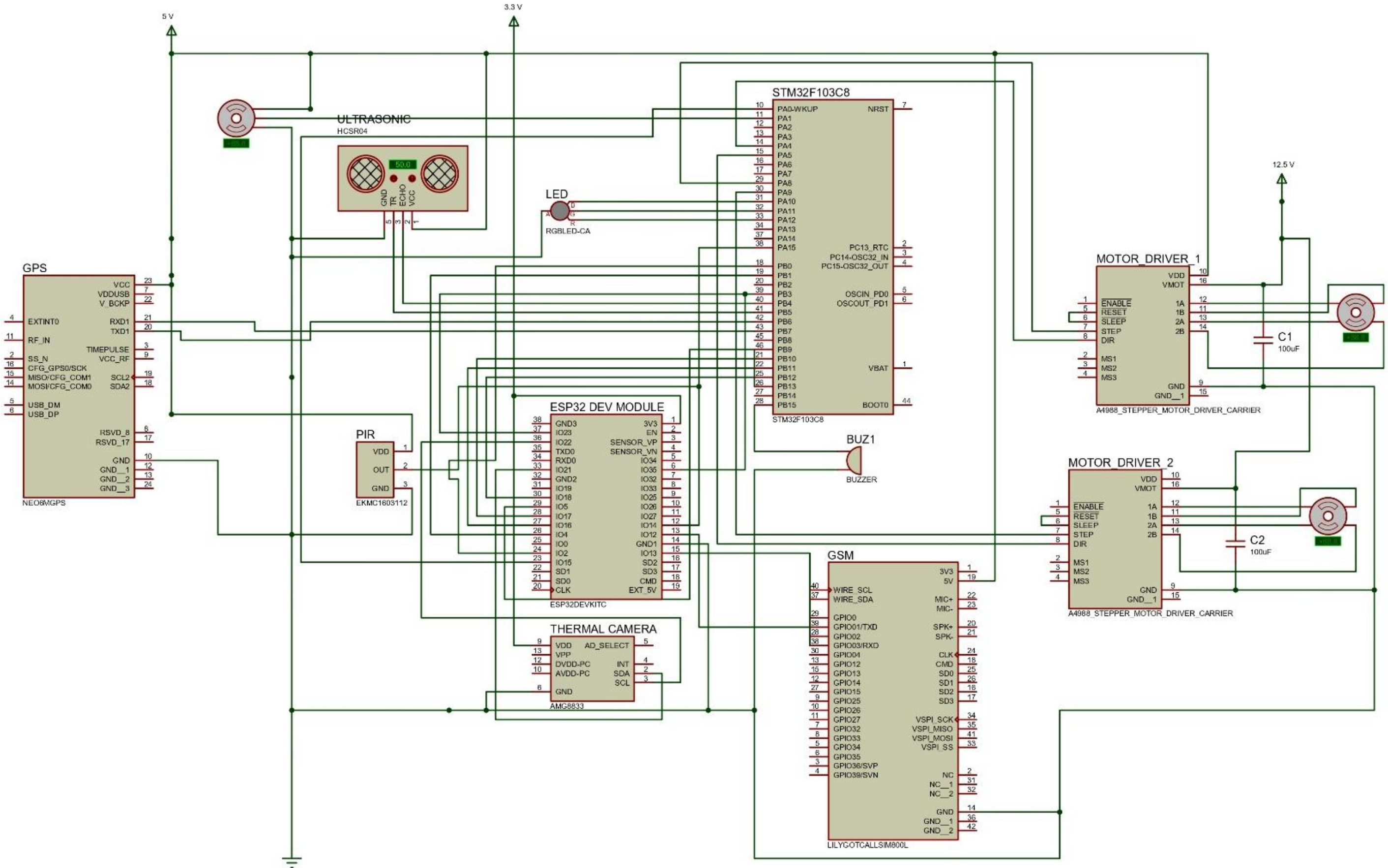
The chassis: modular and robust, allowing quick repairs or part replacements in the field. A monocoque structure (integrated body and frame) can reduce weight and increase strength. In addition to that, it features enclosed compartments for electronics to protect them from dust, water, and impact.

Wheels: They are tread to maximize traction and to maneuver obstacles.

Drive System: Independent motors to maximize maneuverability in tight or cluttered spaces.

Structural Considerations: Critical joints and mounting points are reinforced and printed with high temperature.

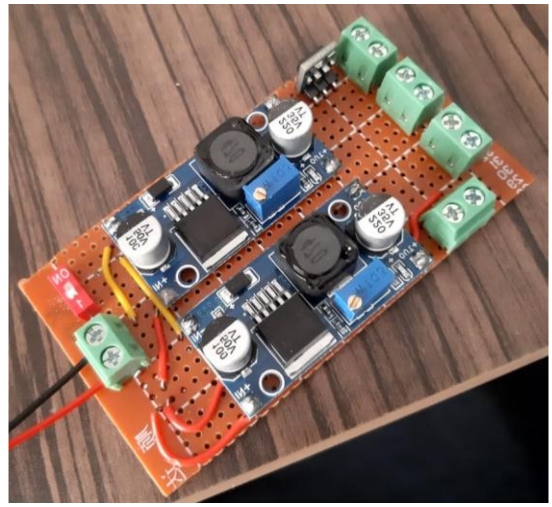
4.3 Electrical & Electronics



The system utilizes:

- Power Delivery Circuit (Buck converters, LDO, Li batteries)
- Microcontroller (STM32F103C8, ESP 32 DEV module.)
- Sensors (Ultrasonic sensor, thermal camera, PIR motion sensor and Gyroscope)
- Motors (Servo motors, Stepper motors, Stepper motors drivers)
- Interface (Buzzer, RGB LED)
- Communication (GPS module, GSM *(Global System for Mobile Communications)* module)

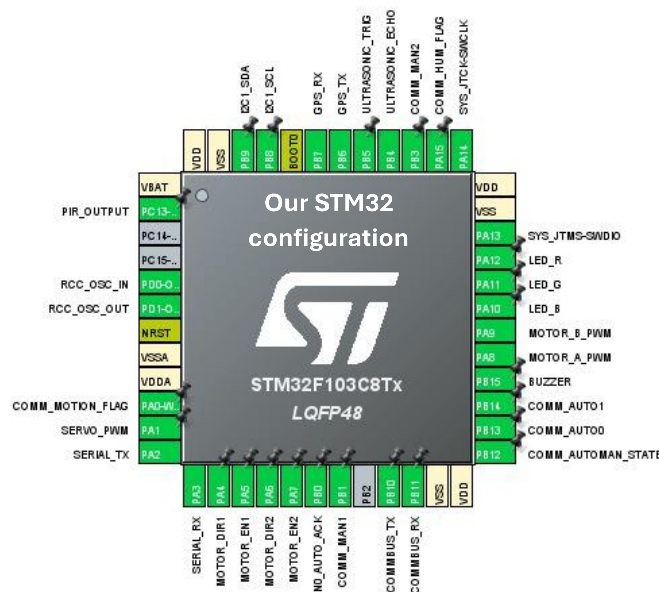
4.3.1 Power Delivery Circuit



Our main power supply is a 12.5 V bundle of 3 Li batteries. This supply is then down converted and regulated via 2 buck converters and an LDO to 5 V, 4 V and 3.3 V, respectively.

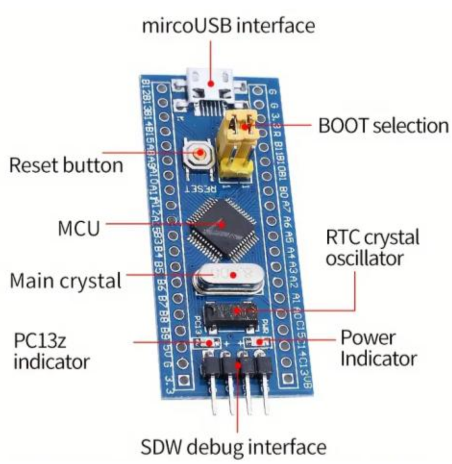
We prioritized buck converters for their exceptional power efficiency (typically 85–95%), which minimizes energy loss and heat dissipation—critical when stepping down large voltage differentials (e.g., 12V to 5V). Unlike linear regulators, which waste excess voltage as heat, buck converters actively switch to regulate output, ensuring optimal performance for power-intensive rover systems. This efficiency extends battery life and reduces thermal management challenges, making them ideal for sustained operation in rescue missions.

4.3.2 Microcontrollers

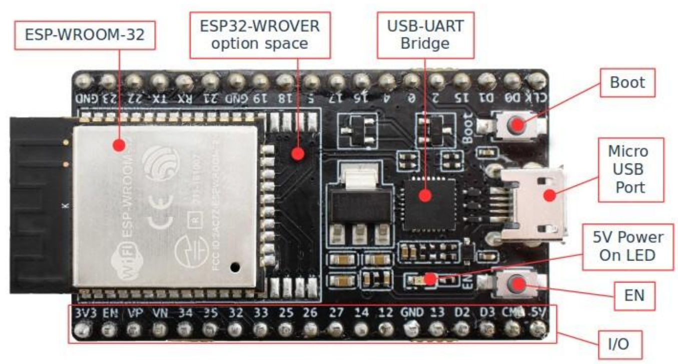


STM32F103C8 is the main microcontroller in our system that was configured to use with most of the electronics included in the rover. These electronics include everything except the GSM module and thermal camera.

We found it computationally complex to optimize some components with STM. This pushed us towards using ESP32 microcontroller with the remaining components. This may have led to the need to configure the two microcontrollers together. However, that is more efficient than configuring STM with the other components.



STM32F103C8



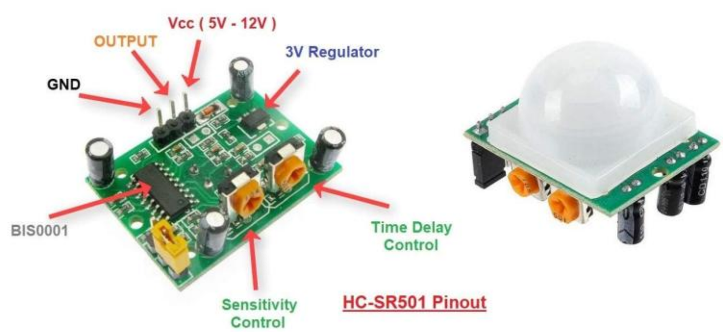
ESP32 dev module

4.3.3 Sensors

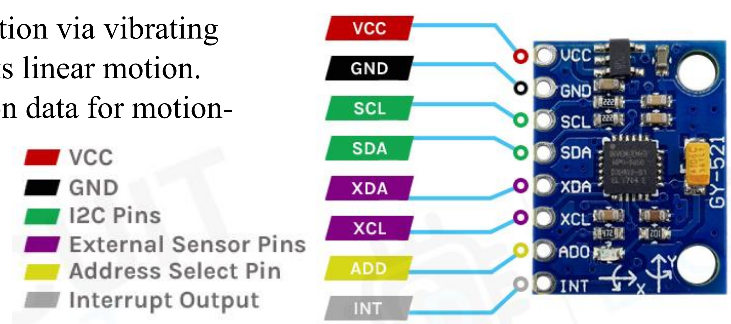
An ultrasonic sensor measures distance by sending high-frequency sound waves and timing how long they take to bounce back. It calculates distance using the echo's travel time and the speed of sound, providing contactless detection for obstacles or objects. Ultrasonic sensor in our system is vital for the obstacle avoidance algorithm by scanning the surrounding terrain.

The AMG8833 Thermal camera is an infrared grid-eye sensor that detects heat signatures using a 8x8 pixel array. It measures surface temperatures by capturing thermal radiation, enabling non-contact temperature mapping for applications like obstacle detection in darkness which would again contribute to our traversal algorithm. However, the main purpose of the thermal camera in our system is to detect injured personnels. ESP was configured with the thermal camera via SDA and SCL.

The SR501 PIR *(passive Infra-Red)* sensor detects motion by sensing changes in infrared radiation (body heat) within its range. When a warm object moves across its field of view, it triggers a signal into the microcontroller. This would help us detect any motion in the surroundings and therefore determine the location of the injured during disasters.



The **MPU-6050 IMU gyroscope** measures rotation via vibrating MEMS structures, while its accelerometer tracks linear motion. Combined, they provide real-time 3D orientation data for motion-sensitive applications. It is configured with STM via SDA and SCL.

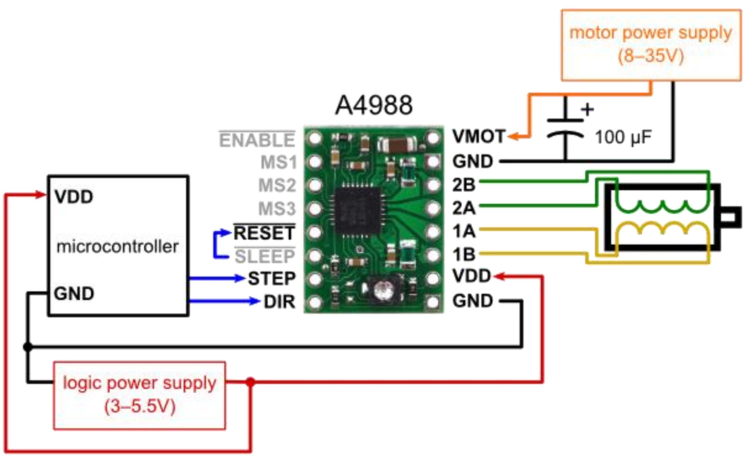


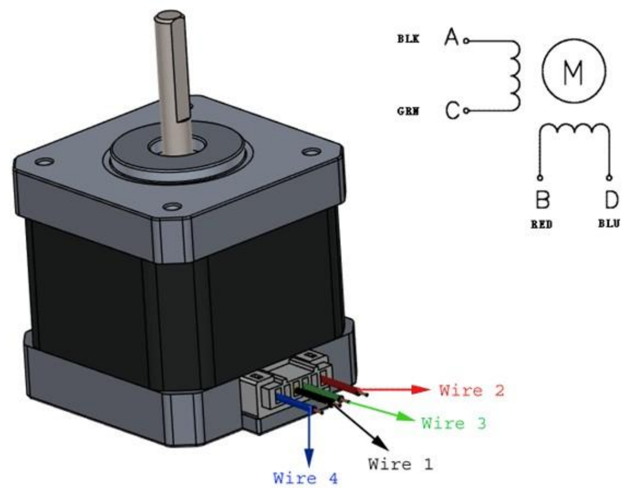
4.3.4 Motors

The system utilizes two types of motors: Servo and stepper

G90 Servo motors are fixed on the top front side of the rover and are used to alter the direction of the ultrasonic sensor and the thermal camera providing a 360° field of view for the sensors.

For Rover motion, we initially considered DC motors at the beginning of the design. However, on further inspection, we have found that **stepper motors** prove to be a better option given their extremely high precision as well as high Torque. We settled for NEMA17 stepper motors with a precise 1.8° step control and A4988 driver.





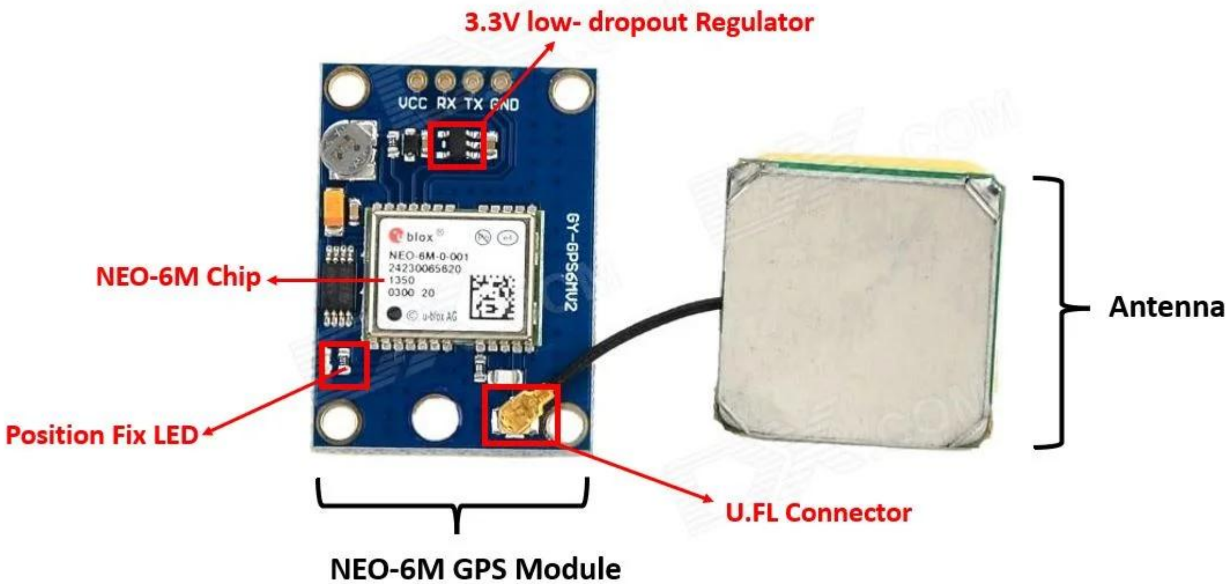
4.3.6 Interface

The rover's buzzer and RGB LED work together to accelerate rescues. By indicating and communicating the rover's current mode of operation and state—the buzzer broadcasts the rover's location with loud tones that changes according to the state of the rover, while the RGB LED provides clear visual cues through colors that depends on the rover's state.

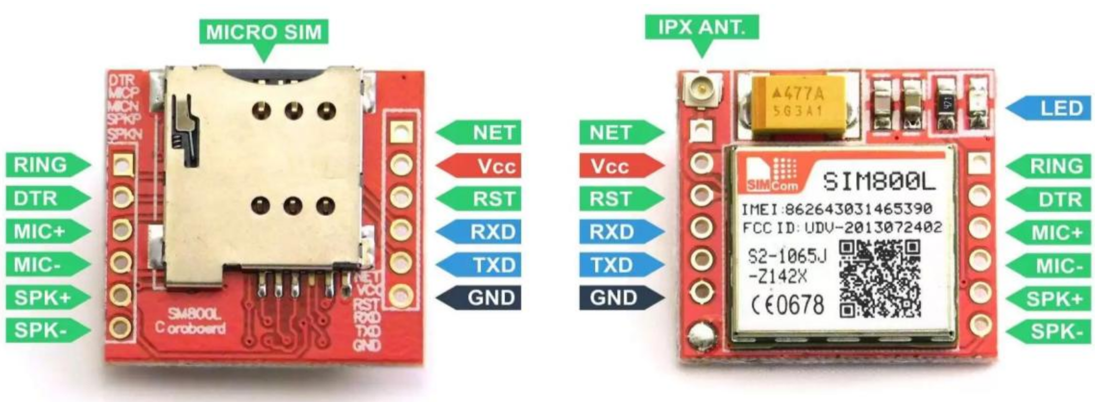
This dual audio-visual system ensures survivors and responders can locate the rover even in smoke, debris, or nighttime conditions, drastically reducing search time in the presence of rescue teams.

4.3.5 Communication modules

The **Neo-6M GPS module** is a high-performance GPS receiver that provides accurate location data (latitude/longitude), altitude, and speed using satellite signals. With low power consumption and fast signal acquisition. It is critical to our system that the GPS module provides continuous feed of the rover location. It is configured with STM via RX and TX.



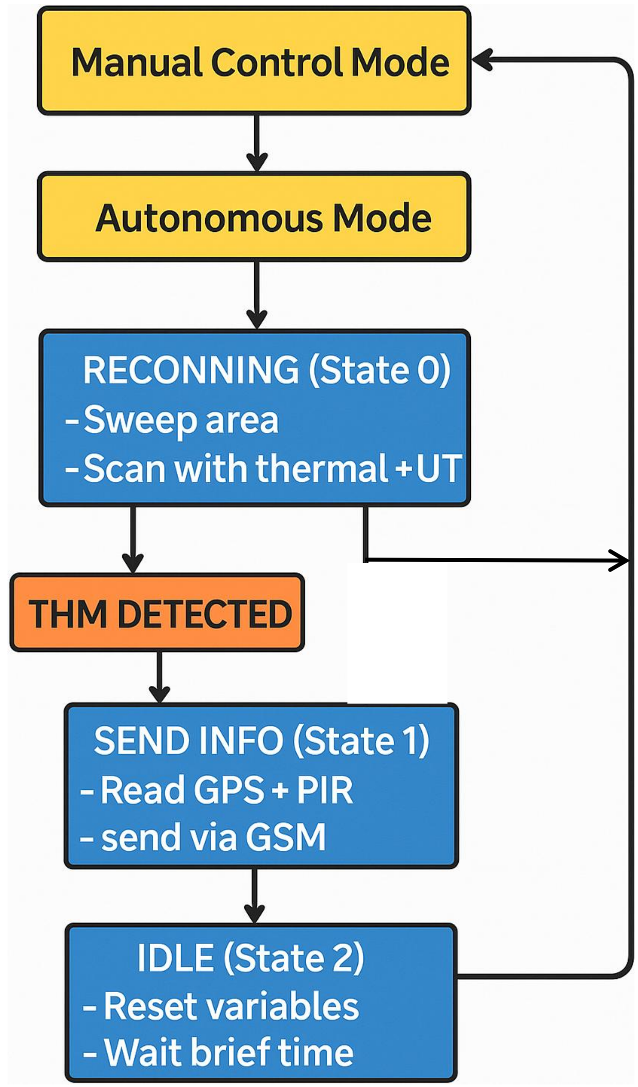
The SIM800L GMS is a compact quad-band module that enables voice calls, SMS, and internet connectivity (via AT commands) for remote communication. It will be needed for communication purposes with the rover. We found that GSM may occasionally draw high currents from the power circuit and for that we have used thicker wires to avoid overloading currents. It is configured with ESP32 via RX and TX.



4.4 Software & Control

4.4.1 Finite state machine

There are two modes of operation for the rover:



<u>Autonomous mode:</u>

1. RECONNING (state 0)
    - Drives forward
    - Sweeps with ultrasonic and thermal sensor
    - Avoids obstacles if detected (obstacle avoidance algorithm).
    - If a human is detected, go to SEND_INFO
2. SEND_INFO (state 1)
    - Stops the rover
    - Gets GPS location
    - Uses PIR to determine if human is moving
    - Sends location in an SMS via GSM to operators and concerned authorities.
    - Goes to IDLE
3. IDLE (state 2)
    - LED stays green
    - Short delay
    - Resets variables
    - Returns to RECONNING

<u>Manual mode:</u>

1. Overrides autonomous mode
2. ESP32 accepts Wi-Fi input
3. Controls:
    - Drive (FWD/BWD/LEFT/RIGHT)
    - Camera rotation
4. LED shows steady blue & BUZZER is silent.

FSM system flow code:

```
void SystemFlow_Run(){

    control_state = Get_Ctrl_State();
    if(control_state == STATE_AUTO) {
        switch (sys_auto_state) {
            case RECONNING:
                Handle_AutoState_Reconning();
                break;
            case SEND_INFO:
                Handle_AutoState_SendInfo();
                break;
            case IDLE:
                Handle_AutoState_Idle();
        }
        Set_Auto_State(sys_auto_state);
        HAL_Delay(100);
    }
    else if(control_state == STATE_MANUAL){

        sys_manual_state = Get_Man_Stat();

        switch (sys_manual_state) {
            case DRV_STOP:
                Handle_ManualState_DRV_STOP();
                break;
            case DRV_FWD:
                Handle_ManualState_DRV_FWD();
                break;
            case DRV_BWD:
                Handle_ManualState_DRV_BWD();
                break;
            case DRV_RIGHT:
                Handle_ManualState_DRV_RIGHT();
                break;
            case DRV_LEFT:
                Handle_ManualState_DRV_LEFT();
                break;
        }
        HAL_Delay(20);
    }


}
```

4.4.2 Algorithms

All algorithms included in the rover’s software exist exclusively in state 0 of FSM which is the reconning state. There are two main algorithms:

1. Reconning:

```c
static void Handle_AutoState_Reconning(void){

    Stepper_MoveForward(ROVER_SPEED);

    uint32_t start_time = HAL_GetTick();
    while(HAL_GetTick() - start_time < TIME_BETWEEN_SWEEPS){
        MANUAL_CONTROL_CHECK();
        thm_state = Get_THM_HUM();
        HAL_Delay(10);
        HANDLE_HUMAN_DETECTION();

        int dist = Get_Average_Distance();
        if (dist < 45) {
            Avoid_Obstacle();
        }
    }

    MANUAL_CONTROL_CHECK();

    Stepper_Stop();
    // Look to the right
    for(uint8_t ang = 90; ang > 0; ang -= 5){

        MANUAL_CONTROL_CHECK();

        Servo_SetAngle(ang);
        thm_state = Get_THM_HUM();
        HAL_Delay(50);
        HANDLE_HUMAN_DETECTION();
    }
    // Look to the left
    for(uint8_t ang = 0; ang < 180; ang += 5){

        MANUAL_CONTROL_CHECK();
        Servo_SetAngle(ang);
        thm_state = Get_THM_HUM();
        HAL_Delay(30);
        HANDLE_HUMAN_DETECTION();
    }
    for(uint8_t ang = 180; ang > 90; ang -= 5){

        MANUAL_CONTROL_CHECK();

        Servo_SetAngle(ang);
        thm_state = Get_THM_HUM();
        HAL_Delay(30);
        HANDLE_HUMAN_DETECTION();
    }
}
```

2. Obstacle avoidance

```c
static void Avoid_Obstacle(void){
    volatile uint8_t Right_Distance = 0.0;
    volatile uint8_t Left_Distance = 0.0;


    Stepper_Stop();
    // Look to the right
    for(uint8_t ang = 90; ang > 0; ang -= 10){

        MANUAL_CONTROL_CHECK();

        Servo_SetAngle(ang);
        HAL_Delay(50);
    }
    HAL_Delay(200);
    Ultrasonic_Read();
    Right_Distance = Get_Average_Distance();

    // Look to the left
    for(uint8_t ang = 0; ang < 180; ang += 10){

        MANUAL_CONTROL_CHECK();

        Servo_SetAngle(ang);
        HAL_Delay(50);
    }
    HAL_Delay(200);
    Ultrasonic_Read();
    Left_Distance = Get_Average_Distance();


    Servo_SetAngle(90);
    HAL_Delay(200);

    // Backing a bit to be able to rotate
    Stepper_MoveBackward(200);
    HAL_Delay(1000);
    Stepper_Stop();

    // Deciding to turn right or left
    if(Right_Distance >= Left_Distance){
        Stepper_TurnRight(400);
    }
    else {
        Stepper_TurnLeft(400);
    }

    HAL_Delay(3000);
    Stepper_Stop();

    HAL_Delay(300);
    // Moving in the direction of more space
    Stepper_MoveForward(ROVER_SPEED);

}
```

4.4.3 Communication protocols

There are two main communication protocols used for the rover:

1. UART

Used for communication between STM32 and ESP32, interfacing with GSM and interfacing with GPS module.

2. I2C

Used for interfacing with thermal camera and Gryoscope.

4.5 Safety & Reliability Considerations

To ensure the rover operates safely and reliably in hazardous environments, we considered the following:

4.5.1 Sensor Redundancy

The system cross-validates data from PIR and thermal camera to ensure accurate survivor detection while minimizing false readings. If one sensor fails, the other maintains critical detection capability.

4.5.2 Environmental Protection

Durable 3D-printed enclosures shield sensitive electronics from dust, moisture, and physical impacts. The ventilated mesh design provides passive cooling to prevent overheating during extended operations.

4.5.3 Communication Systems

Reliability of the Dual GSM/GPS modules can be tricky since it mainly depends on the network provider and satellites whose parameters can fluctuate heavily in no clear manner. In other words, there are no direct methods for solving this problem from the rover’s side.

4.5.4 Operational Safety

All 3D-printed components use smooth, rounded designs to eliminate sharp edges. The integrated buzzer and RGB LED provide clear audible and visual indicators of the rover's profile.

5. Implementation

5.1 Fabrication & Assembly process

5.1.1 Mechanical

1. The chassis, wheels, and protective lids were fully 3D-printed using lightweight yet durable PLA to balance strength and weight.
2. Stepper Motors were installed at the front corners of the chassis for a front wheel drive rover.

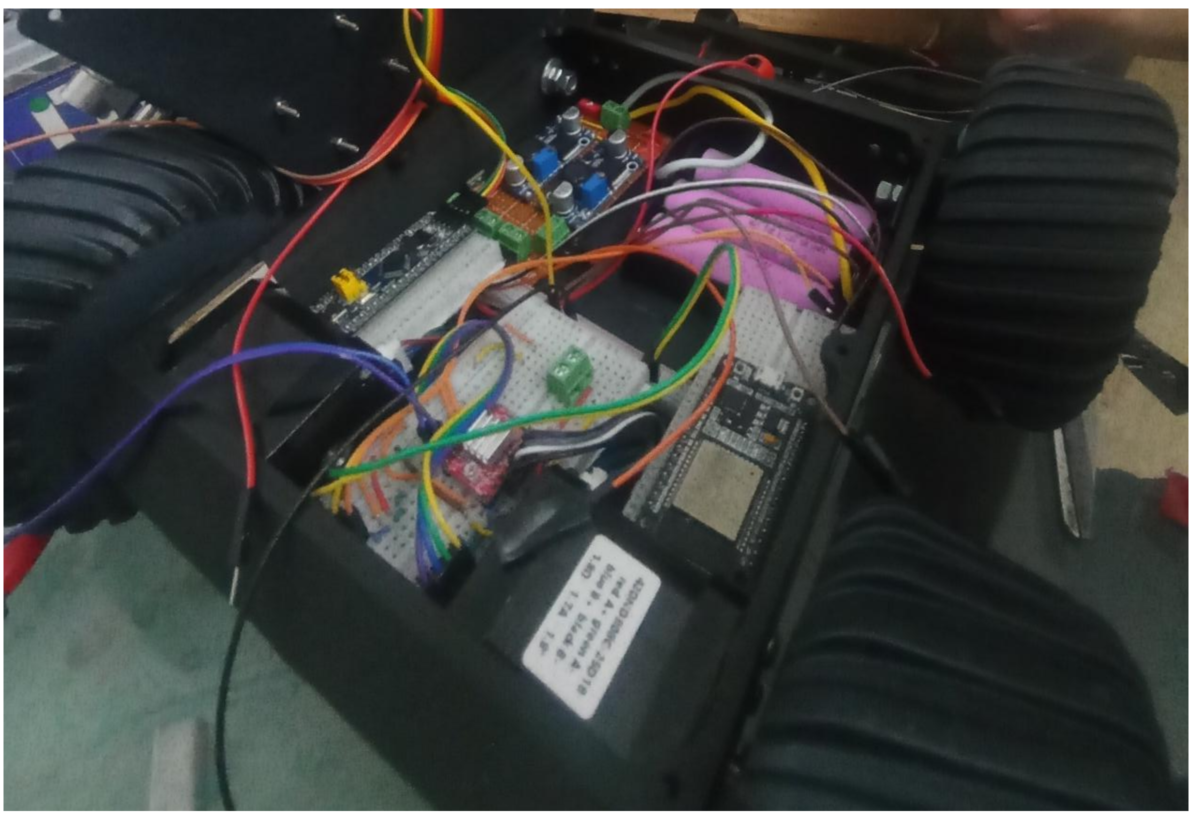
5.1.2 Electrical

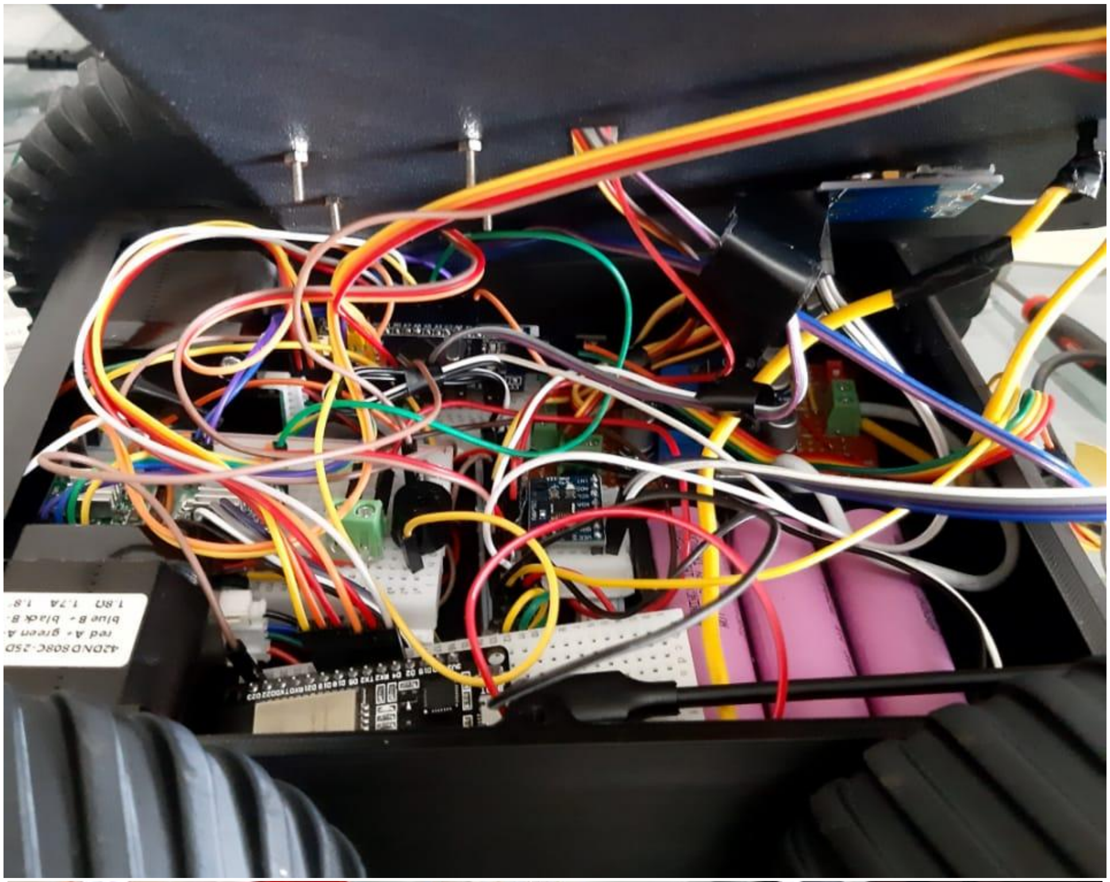
1. Pins were precision-soldered onto their respective PCBs.

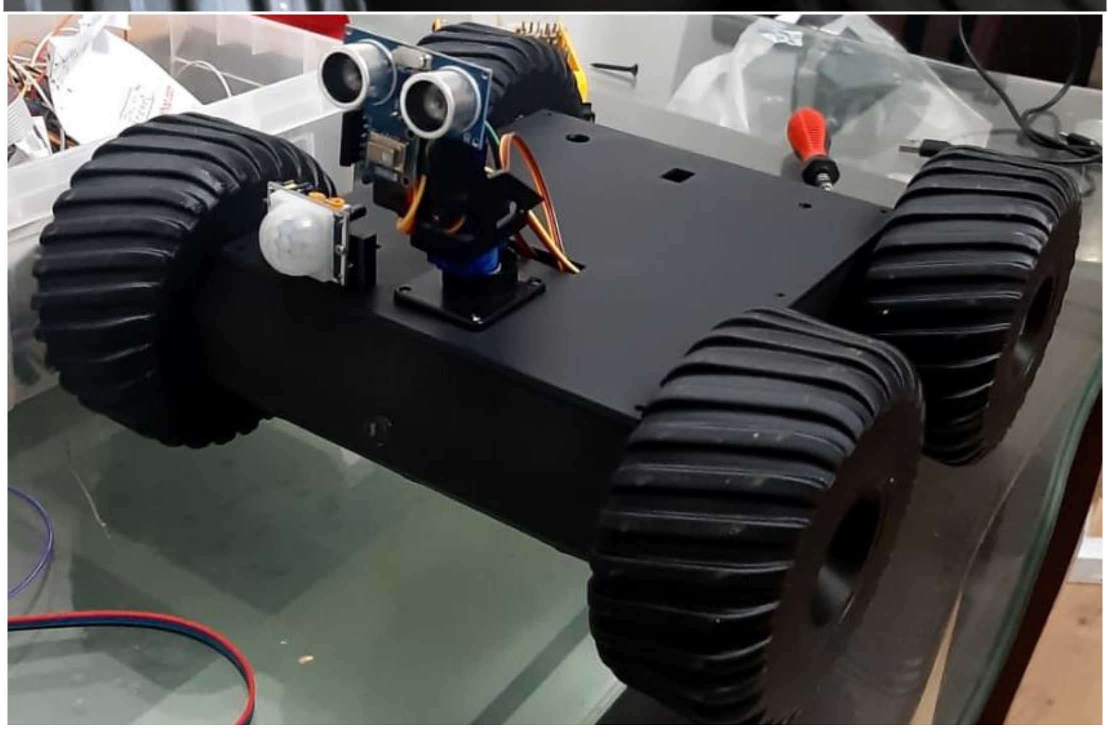
2. Each module (e.g., motor drivers, sensor interfaces) was first tested individually on separate breadboards to verify functionality.

3. Each Breadboard with its module is then placed in the cavity and integrated with the other breadboards.

4. The servo motors, thermal camera (AMG8833), and ultrasonic sensor were mounted on the rover’s front top plate







During Electronics assembly process

5.2 Challenges faced & Solutions

1. DC Motors required high current to function, so to overcome, we switched to NEMA 17 stepper motors.

2. High complexity of implementing communication driver between STM32 and ESP32 using UART and 3-way handshake concept. The solution is simple: Just turning inro a more simplified driver using GPIO based flagging

3. The limited processing power in stm32 to run human detection algorithms in thermal imaging. So, we used esp. 32 which is more powerful regarding computing ability.

6. Testing & Results

After Testing indoors and outdoors in different circumstances, we have verified that the power delivery system, the sensors' system, the processor system and the communication system all work collectively.

7. Discussion

7.1 Analysis of Results

The fully autonomous 3D-printed search and rescue rover demonstrated promising performance in simulated disaster environments. Key achievements include:

- **Adaptive Mobility**: The rover successfully navigated rough and uneven terrains, leveraging its treaded wheels and independent stepper motors. The front-wheel drive configuration proved effective for maneuverability in cluttered spaces.
- **Multi-Modal Target Identification**: The integration of thermal imaging (AMG8833), ultrasonic sensors (SR04), and PIR motion sensors (SR501) enabled accurate detection of survivors, even in low-visibility conditions. Cross-validation between sensors minimized false positives.
- **Real-Time Communication**: The GSM (SIM800L) and GPS (Neo-6M) modules reliably transmitted victim coordinates and environmental data to emergency teams, though signal stability occasionally depended on external factors like network coverage.
- **Autonomous Navigation**: The finite state machine (FSM) and obstacle avoidance algorithms allowed the rover to operate autonomously, transitioning seamlessly between RECONNING, SEND_INFO, and IDLE states.

However, some challenges were noted:

- The dual-microcontroller setup (STM32F103C8T6 and ESP32) introduced minor latency in data processing, particularly during sensor fusion.
- Environmental factors such as extreme temperatures or dense debris occasionally affected sensor accuracy.

7.2 Limitations

- Power Consumption: The rover's high-power components (e.g., stepper motors, GSM module) limited battery life during extended missions.
- Communication Reliability: GSM performance varied in areas with poor network infrastructure, delaying data transmission.
- Sensor Range: The thermal camera's 8x8 resolution restricted detailed heat mapping at longer distances.
- Weight Distribution: The front-heavy design occasionally reduced traction on steep slopes.

7.3 Potential Upgrades

To enhance future iterations, the following upgrades are proposed:

- Energy Efficiency: Replace Li batteries with higher-capacity lithium-polymer packs or integrate solar panels for recharging.
- Advanced Sensors: Upgrade to a higher-resolution thermal camera (e.g., 32x24 grid) and add LiDAR for improved obstacle detection.
- Redundant Communication: Incorporate LoRa or satellite modules as backup for GSM in remote areas.
- Modular Design: Enable swappable sensor modules or payloads (e.g., gas detectors, medical supplies) for mission-specific adaptability.
- Machine Learning: Implement AI-driven path optimization and survivor classification to reduce false alarms.

8. Conclusions

This project successfully designed and implemented a fully autonomous 3D-printed search and rescue (SAR) rover for disaster response operations. The rover demonstrated its capability to navigate challenging terrains, detect survivors through multi-sensor fusion, and relay critical information to emergency teams in real time. Key achievements include:

- Effective Mobility: The 3D-printed chassis and treaded wheels, combined with stepper motors, provided reliable traversal over uneven and debris-laden environments.
- Accurate Victim Detection: The integration of thermal imaging, ultrasonic sensors, and PIR motion detection enabled robust identification of survivors, even in low-visibility conditions.
- Autonomous Operation: The finite state machine (FSM) and obstacle avoidance algorithms allowed the rover to function independently, optimizing its path and ensuring efficient coverage of disaster zones.
- Real-Time Communication: GPS and GSM modules facilitated timely transmission of victim coordinates and environmental data, enhancing coordination with rescue teams.

Despite these successes, the project highlighted areas for improvement, such as power consumption, sensor resolution, and communication reliability in remote areas. Future work will focus on integrating higher-capacity power systems, advanced sensors, and redundant communication modules to further enhance the rover's performance.

In conclusion, this SAR rover represents a significant step toward leveraging autonomous robotics for life-saving missions in hazardous environments. Its modular and scalable design ensures adaptability for diverse disaster scenarios, offering a practical and cost-effective solution to augment traditional rescue efforts. The lessons learned and insights gained from this project lay a strong foundation for future innovations in the field of search and rescue robotics.

9. Acknowledgements

Abdelrahman Abougendia + Fouad Hasheesh

- System Design
- Communication Protocol between STM32 and ESP32
- Driver Implementation for the following components:
    - GPS module
    - Thermal Camera
    - GSM module

Salah Elsayed + Mohamed Farouk

- Worked on Power Delivery
- Implemented Servo motor driver
- Implemented Ultrasonic Driver
- Worked on Reconning Algorithm
- Project Schematics
- Project Report

Jana Sherif + Rokaya Radwan

- Implemented Stepper Motor-Driver driver
- Implemented Alerts driver
- Implemented Gyroscope driver
- Project Presentation

Sara Aldahshan + Habiba Ahmed

- Manual Control Mode
- Implemented PIR motion sensor driver
- Rover Application

Amir Ashraf + Nour Hazem

- Chassis re-Design for 3D printing
- Implemented Obstacle Avoidance Algorithm

10. References

1. Adafruit Industries. (2019). *AMG8833 IR thermal camera breakout*. Adafruit Industries LLC.
2. Advanced Monolithic Systems. (2017). *AMS1117 1A low dropout voltage regulator* (Rev. 5.2) [Datasheet]. http://www.advanced-monolithic.com/pdf/ds1117.pdf
3. Allegro MicroSystems. (2019). *A4988 microstepping driver with translator and overcurrent protection* (Rev. 4) [Datasheet]. https://www.allegromicro.com/~/media/Files/Datasheets/A4988-Datasheet.ashx
4. BISS. (2014). *HC-SR501 PIR motion detector* [Datasheet]. https://www.mpja.com/download/31227sc.pdf
5. CUI Devices. (2020). *Magnetic buzzer specifications*. https://www.cuidevices.com/product/resource/pdf/cmt-8540s-smt-tr.pdf
6. Cytron Technologies. (2013). *HC-SR04 ultrasonic sensor* [Datasheet]. http://web.eece.maine.edu/~zhu/book/lab/HC-SR04%20User%20Manual.pdf
7. Espressif Systems. (2023). *ESP32 series datasheet* (Version 4.8) [Datasheet]. https://www.espressif.com/sites/default/files/documentation/esp32_datasheet_en.pdf
8. Espressif Systems. (2023). *ESP32-DevKitC V4 getting started guide* (Version 1.9). Espressif Systems (Shanghai) Co., Ltd.
9. InvenSense Inc. (2013). *MPU-6000 and MPU-6050 product specification* (Rev. 3.4) [Datasheet]. https://invensense.tdk.com/wp-content/uploads/2015/02/MPU-6000-Datasheet1.pdf
10. Kingbright Corporation. (2019). *RGB LED 5mm common cathode diffused*. Kingbright Electronic Co., Ltd.
11. National Electrical Manufacturers Association. (2018). *NEMA 17 stepper motor specifications* [Standard ICS 16-2018]. NEMA Standards Publication.
12. Panasonic Corporation. (2017). *AMG88xx Grid-EYE infrared array sensor* (Rev. 1.1) [Datasheet]. https://cdn-learn.adafruit.com/assets/assets/000/043/261/original/Grid-EYE_SPECIFICATIONS%28Reference%29.pdf
13. Pololu Corporation. (2017). *A4988 stepper motor driver carrier*. Pololu Corporation.
14. SIMCom Wireless Solutions. (2014). *SIM800L GSM/GPRS module* [Datasheet]. SIMCom Wireless Solutions Co., Ltd.

15. SIMCom Wireless Solutions. (2016). *SIM800L hardware design* (Version 1.02) [Design guide]. https://simcom.ee/documents/SIM800L/SIM800L_Hardware%20Design_V1.02.pdf

16. STMicroelectronics. (2015). *STM32F103x8/STM32F103xB medium-density performance line ARM®-based 32-bit MCU* (Rev. 18) [Datasheet]. https://www.st.com/resource/en/datasheet/stm32f103c8.pdf

17. STMicroelectronics. (2021). *STM32F103C8T6 ARM Cortex-M3 microcontroller reference manual* (RM0008 Rev. 21). STMicroelectronics N.V.

18. TDK InvenSense. (2013). *MPU-6000/MPU-6050 register map and descriptions* (Rev. 4.2) [Register map]. TDK Corporation.

19. Texas Instruments. (2013). *LM2596/LM2596S SIMPLE SWITCHER® 3-A step-down voltage regulator* (Rev. P) [Datasheet]. https://www.ti.com/lit/ds/symlink/lm2596.pdf

20. TowerPro Co., Ltd. (2015). *SG90 servo motor technical specifications*. TowerPro Co., Ltd.

21. u-blox AG. (2011). *NEO-6 u-blox 6 GPS modules* (UBX-13003947 Rev. A1) [Datasheet]. https://www.u-blox.com/sites/default/files/products/documents/NEO-6_DataSheet_%28GPS.G6-HW-09005%29.pdf