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*Original Article*

# Design and Development of a Miniature Autonomous Rover for Exploration and Rescue Operations

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***Abstract* - *The Rover, considered a robotic vehicle used in space missions to explore and gather data on extraterrestrial surfaces such as the Moon or Mars, is equipped with instruments and sensors to perform various tasks, such as collecting and obtaining data and images of samples. Sojourner, the first exploration robot launched to Mars in 1997 by NASA researchers, was characterized by its microwave oven-sized design and data collection that marked the beginning of the study of the planet Mars. Likewise, following the same idea, the present project consists of the design and implementation of a remotely controlled Rover-type exploration robot, which allows access to the collection of important data for taking necessary and immediate measures in emergency situations. As a result, the implementation of an autonomous vehicle with real-time data and image visualization through a base station or mobile device was achieved. Due to its small and robust size, it has the capability to enter complex and difficult-to-access locations for rescue or first aid personnel. Additionally, the vehicle is equipped with environmental sensors for data collection and uses LIDAR for navigation and obstacle detection. Finally, it sends images of the environment and has an alternative power source through solar energy.*

***Keywords* - *Rover, Robotic vehicle, Exploration, Rescue missions, LIDAR sensor, Solar panels.*

## 1. Introduction

Interplanetary missions are increasingly gaining momentum and are more valued by governmental and/or private space agencies. One of the main concerns often present in exploration lies in understanding the environment and surroundings in certain places where humans cannot access. This issue is not only evident in space exploration but also extends to any environment hostile to humans, such as areas contaminated by toxic or radioactive materials. On the other hand, the so-called “ROVERS” are autonomous or semi-autonomous robotic exploration systems that have the ability to receive instructions, perform measurements, take samples, and even analyze, process, and report on tasks assigned. These devices have proven to be efficient and competent enough for fieldwork, including rescue teams and reconnaissance in hazardous areas. Moreover, they serve as a good tool and opportunity to apply acquired knowledge and delve further into the understanding of technology and space development.

From a broader perspective, Unmanned Ground Vehicles (UGVs) are crucial in both planetary exploration and rescue missions. Brian Ernesto Mori Virhuez [1] note that traditional search and rescue operations are risky because human rescuers must enter unstable environments after disasters like earthquakes. Robotic systems help reduce the direct exposure of rescue personnel, enhancing safety and operational efficiency. Sánchez Muyulema [2] emphasizes that rescue robotics involves careful analysis of communication systems, structural design, locomotion, and sensing technologies, as these factors determine the effectiveness of robotic platforms in disaster situations. The development of autonomous and semi-autonomous ground vehicles has been widely studied. Carlosama Fauta [3] mentions that these vehicles are used in search and rescue, exploration, and surveillance, although their complexity can increase production costs. Nonetheless, the study shows that cost-effective solutions can still provide functional autonomy in real applications.

Additionally, Blancas Arce et al. [4] developed the AR17 UGV prototype inspired by biological systems, concluding that such technologies allow for quick access to hazardous areas while minimizing risks for human rescuers through remote inspection and situational awareness. Environmental factors also significantly impact the design of rescue robotics.

Mori Virhuez [5] highlights that rescue operations in regions like Peru are greatly affected by geographical and weather conditions, which limit the accessibility and operational range of robotic systems. Recent developments in robotics have increasingly incorporated advanced sensing, communication, and Castro computation technologies. In [6] year 2021, Miguel Alfredo, in his graduation work, describes that his proposal is a Cloud IoT architecture oriented to mobile robotics and is also capable of image recognition through Cloud Computing, demonstrating the benefit of exploration by the robot. The results were satisfactory, with correct identification of hardware dimensions, acceptable performance of the components responsible for movement, and it proved to be scalable for future generations of Edge Computing implementation.

The development of a design project that consisted of creating a prototype of a teleoperated mobile robot were explained. Its function would be to inspect high-risk areas in case of a building collapse. This robot aims to access areas where rescuers cannot enter. Controlled from a secure area, either by means of an external remote control or a computer keyboard. Thus, the robot's initiative will be the rescue of injured people or sending help signals to the rescue personnel.

In [7] Ecuador, in 2019, the Author Mayra Quicaliquin described in her thesis a problem that affects all Ecuadorians. The solution she proposed was the creation of a robot that provides support in situations of natural disasters or earthquakes, and that also helps visualize collapsed structures so that rescuers can take them into account upon entering.

Therefore, the Author considered certain characteristics such as difficult access, the need for lighting in dark places, complex floors, and obstacles in the path. She examined everything from the most basic aspects, such as the theories and regulatory standards that should be considered, to the actual design and potential implementation anomalies. Conclusions were reached that parts of the implementation can be satisfactory, but some meticulous criteria must be met to achieve optimal robot displacement performance.

The web platform was appropriate for the situation, providing user-friendly interaction. Also, the camera used for this project had good image quality, and the wireless range exceeded expectations. The Author recommended that if we want the camera to move 180 degrees horizontally, we could opt for a servomotor.

In [8], Berenice Velasco and Omar Hernández in Mexico, in 2022, began their project by discussing the technological advancements up to the present day, emphasizing the history of robots and how they assist human labor. Their project utilizes an autonomous movement module through specialized technology known as LIDAR or Light Detection and Ranging.

They used LIDAR technology to support other types of research involving this tool; they show how it works and how it is automated. The project consists of components like the Arduino UNO, H-bridge L298N, and the LIDAR Lite v3 Laser Sensor; each of these components was used to create a robotic prototype and will enable an algorithm designed to make the robot move autonomously. The conclusion of the project states that due to the accuracy of the LIDAR sensor and its computational simplicity, it was selected for use in this project. During testing, several timing corrections and movement values were made, and the algorithm's implementation was ultimately considered successful. However, the research aims to introduce an area of opportunity for those who want to exploit advancements with the LIDAR sensor.

In [9], in 2023, Antonio Roldán Gómez developed a final degree project that presents the development of a semi-autonomous mobile robot for the purpose of environment exploration and map generation. The project begins with the requirements analysis to achieve this objective, allowing for the construction of the robot. A notable aspect is the use of a LIDAR sensor, which allows it to be mounted and have a controllable system.

The programming is divided into processes: real-time exploration will be handled by FreeRTOS, map construction and generation will be programmed in Python, and the system control will be done through an Android application developed in Java. The project's conclusions determined a successful outcome, with several challenges being overcome, such as calibration and the LIDAR's behavior, and achieving the essential system objectives. It is also suggested to use higher-quality components and apply more advanced methods to obtain a more efficient result.

From a technological standpoint, further studies highlight the importance of integrating robust sensing, autonomy, and communication in robotic rescue systems. Ortiz Toledo [10] points out that mapping and navigation in mobile robots are complex tasks that depend heavily on calibration quality and sensor integration, as errors can result in inaccurate environmental representations. Similarly, Mantoani et al. [11] stress that future exploration missions, like planetary sample retrieval, require high levels of autonomy to function in remote and uncertain environments, underscoring the importance of autonomous navigation systems for terrestrial rescue scenarios.

The development of an emergency aid robot is technically justified due to its capabilities to access dangerous areas, explore and map affected terrain, transport supplies, facilitate communication, and assist victims. These functions enhance response and rescue efforts by allowing access to places that humans cannot reach, providing real-time information on damage and victims, efficiently delivering supplies, establishing communication in disrupted situations, and offering basic care to those affected.

In emergencies, deploying a Rover-type aid robot can save lives and improve safety. Finally, considering the limitations found in the literature-such as restricted autonomy, environmental sensitivity, and partial integration of perception and navigation systems-this work proposes the design and construction of a specialized Rover robot to assist in emergency situations through search and exploration, providing additional support to rescue teams.

## 2. Methodology

### *2.1. Overall Design and Requirements*

The development of the mini-rover for exploration and rescue missions in Lima utilized a user-centered design approach based on the Design Thinking methodology. This process ensured that the final solution addressed the actual needs of rescue personnel in the context of emergency operations.

The initial empathy phase involved reviewing existing literature and previous technological proposals related to search and rescue operations, which helped identify gaps and justify the need for a solution like the mini-rover. Following this analysis and adhering to the methodology framework of understanding needs, generating ideas, prototyping, and testing solutions [12], a set of key system requirements was established.

These requirements were divided into Functional Requirements (FR), which specify what the system must do, and Non-Functional Requirements (NFR), which outline how the system should perform. These requirements, summarized in Table 1, guided the entire technical development process.

**Table 1. System requirements**

| ID | Type | Requirement Description |
|---|---|---|
| RF-01 | Functional | The rover must operate in two modes: autonomous and manual. |
| RF-02 | Functional | In autonomous mode, the rover must navigate and avoid obstacles using RPLIDAR data. |
| RF-03 | Functional | The rover must establish a Bluetooth connection with the mobile application for control and data exchange. |
| RF-04 | Functional | The system must stream real-time video to the operator via an ESP32-CAM Wi-Fi server. |
| RF-05 | Functional | The rover must measure and transmit environmental data (temp, audio, press, altitude, IR temp) to the app. |
| RF-06 | Functional | The mobile app must provide voice feedback for sensor readings and system status. |
| RF-07 | Functional | The rover must be capable of solar charging via servo-actuated panels, triggered manually or by low battery. |
| RNF-01 | Non-Functional | The control link must have low latency for real-time operation. |
| RNF-02 | Non-Functional | The mechanical design must withstand rough terrain. |
| RNF-03 | Non-Functional | The system must be energy efficient, leveraging solar power for extended mission time. |

### *2.2. System Architecture*

The rover was designed with a dual-mode architecture, including autonomous mode and manual mode, to adapt flexibly to demanding mission conditions.

To support both functionalities, the vehicle incorporated perception and navigation systems, such as proximity sensors, high-resolution cameras, and wireless communication modules.

These systems enabled autonomous navigation for environmental mapping and obstacle detection. In addition, the onboard camera and communication module enabled real-time video transmission to a mobile application, which functions as a remote control station for manual mode.

To ensure prolonged operation in the field, the rover was equipped with an autonomous energy system based on solar panels, which recharge a lithium battery bank.

To allow the rover to traverse over obstacles and have good traction even in extremely rough terrain, the design uses a rocker-bogie suspension system.

The chassis was optimized to provide a good balance of strength and weight to allow improved mobility in confined spaces and on rubble.

An embedded control system with the ability to make autonomous decisions has also been incorporated to allow the rover to carry out its missions without the need for constant human operator involvement. The control system is also equipped with a two-way wireless communication module that provides an option to operate the rover in manual mode. A mobile application can then be used in real-time control of the rover’s operation. The wireless module also provides the human operator with telemetry data and video so that the rover can be monitored and controlled during its missions from outside.

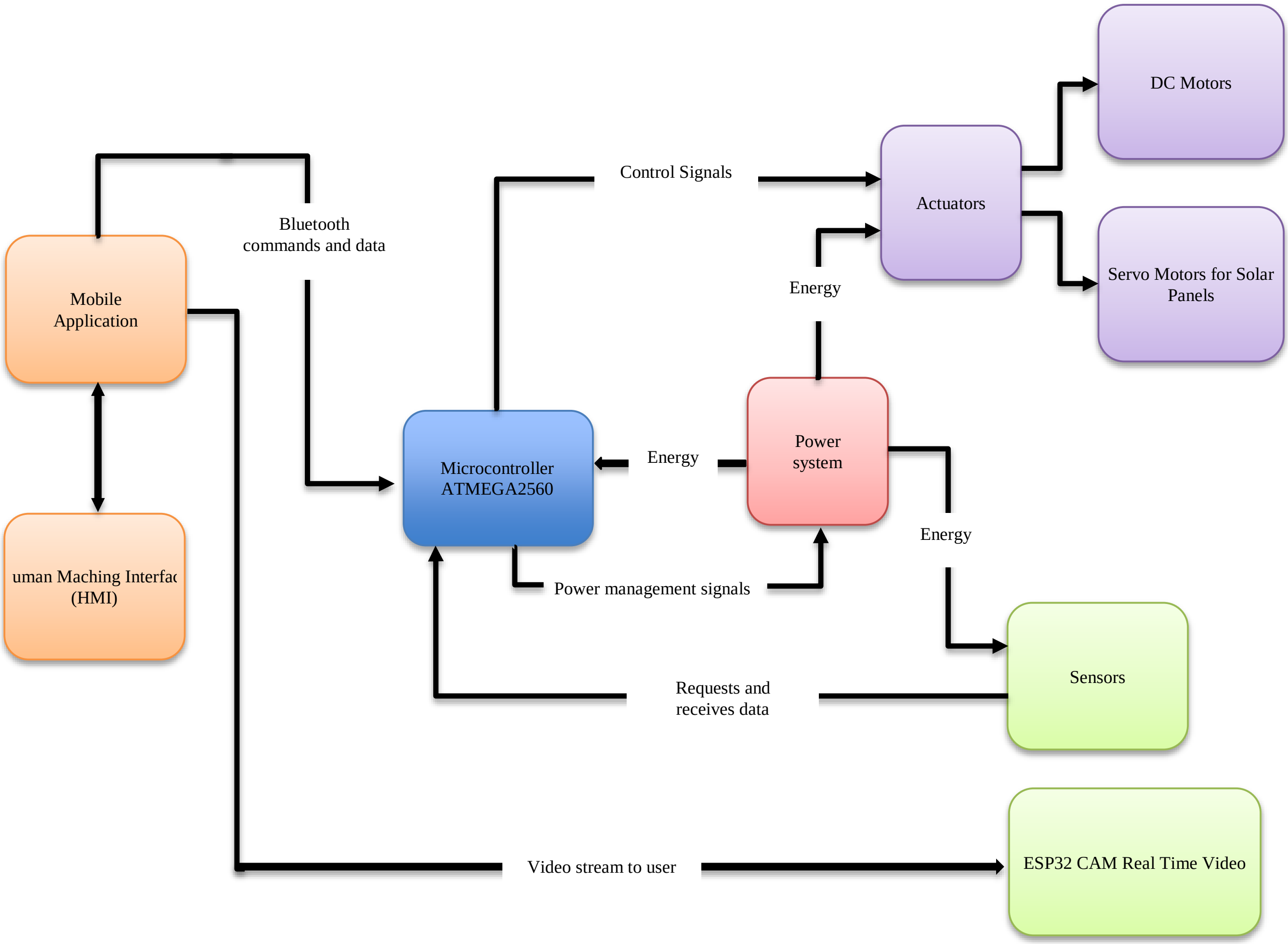


**Fig. 1 System block diagram of the mini-rover architecture**

### *2.3. Hardware Design and Implementation*

#### *2.3.1. Rocker-Bogie*

The Rocker-Bogie suspension system (Figure 2) is a type of suspension used in robotic vehicles, especially in planetary exploration rovers like those sent to the Moon and Mars by NASA. Its design is intended to allow the rover to move efficiently over rough and uneven terrain, overcoming obstacles such as rocks, dunes, or steep slopes without losing stability or traction [13].

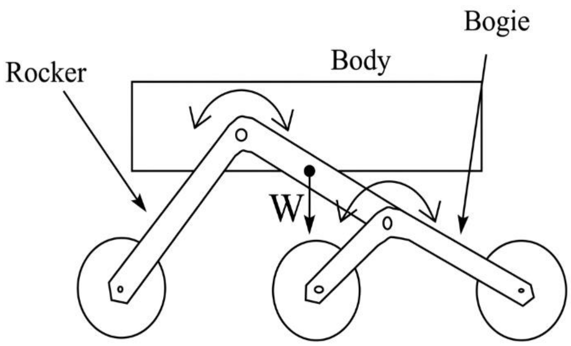


**Fig. 2 Rocker-Bogie suspension system**

*Operation*

- Rocker: This part of the system acts as a swinging arm attached to a fixed structure of the rover. When moving, the rocker can "balance" on the terrain.

- Bogie: This is comprised of a wheel assembly that connects to a rocker and can oscillate as the rocker rotates, keeping the wheels in contact with the ground and enabling the rover to navigate over uneven terrain.

*Advantages*

- Improved mobility: It allows the vehicle to move over uneven terrain, such as rocks and slopes, without losing stability.

- Durability: Its robust design minimizes damage caused by impacts or collisions with obstacles.

- Mechanical simplicity: Although it has multiple moving components, the Rocker-Bogie system is relatively simple and effective for its purpose.

### *2.3.2. Mechanical Design*

Using SolidWorks software, the mechanical modelling of the rover vehicle was performed in a methodical way. Initially, a detailed technical drawing was created, including orthagonal (front/side/top) views (see Figure 3); this serves as the basis for the next construction stage. Next, for each individual component and element of the vehicle, a 3D model was built, thus generating a collection of virtual parts (see Figure 4). Finally, as part of the digitalisation process, the entire assembly of the vehicle was completed, along with an appropriate rendering of the assembly(s) (see Figure 5). By providing a basis for the verification of the rocker system kinematics, confirming that there were no incompatibilities between the parts, and allowing for the visualisation of the entire rover vehicle before the construction phase, 3D modelling assisted greatly in the execution of the rover construction project.

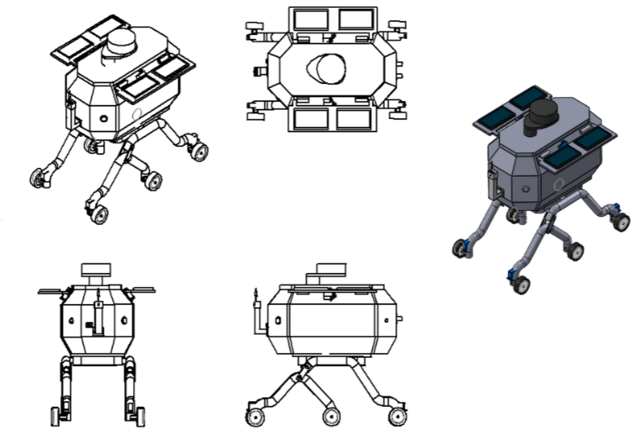


**Fig. 3 Technical drawing of the design in SolidWorks with orthogonal views**

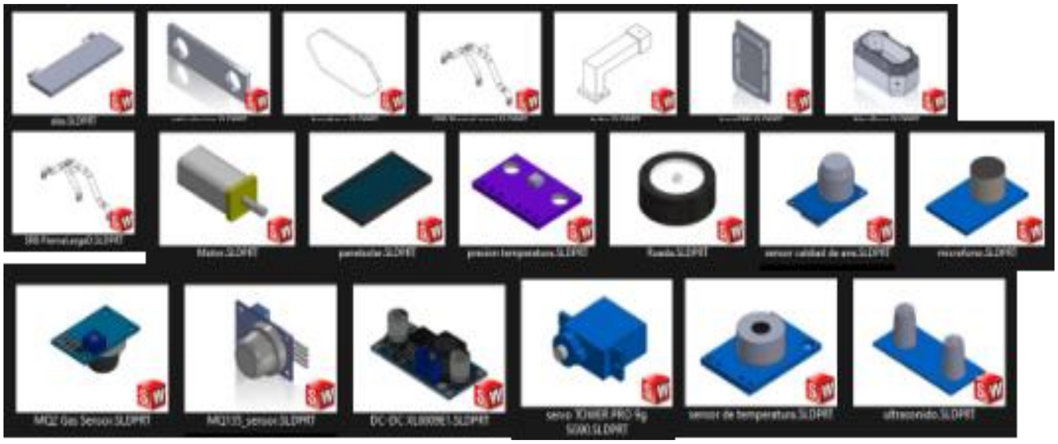


**Fig. 4 Individual parts of the rover structure**

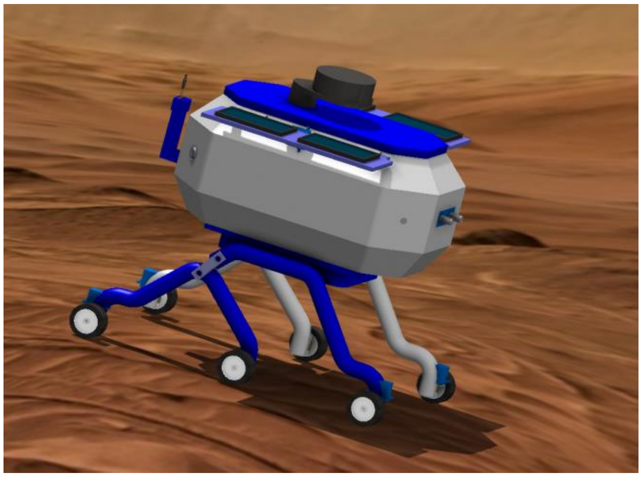


**Fig. 5 Rendered 3D view of the assembled rover model**

After the digitalization process was validated, the components and parts were materialized through 3D printing. This method currently allows the fabrication of parts with considerable geometric complexity while maintaining relatively low production costs.

During the final assembly of the chassis and the suspension (Figures 6 and 7), the accuracy of the digital model was verified. Upon completing the final manufacturing stage, a functional and robust prototype was obtained, ready for the integration of electronic components and subsequent testing procedures, such as mobility tests.

**Fig. 6 Fully assembled chassis and rocker-bogie suspension system**

**Fig. 7 View of the first complete physical assembly of the rover**

*2.3.3. Electronic Design*

The electronic architecture was designed around the Arduino Mega 2560 microcontroller, chosen for its extensive I/O capabilities. The sensing subsystem comprises an RPLIDAR A1M8 for primary navigation and obstacle avoidance, supplemented by an HC-SR04 ultrasonic sensor for short-range object detection and a BME280 for environmental monitoring.

An ESP32-CAM module provides live video streaming, while an HC-06 Bluetooth module handles bidirectional communication with the mobile application for telemetry and control. Operation of the actuators is managed by three H-bridges that control six DC motors for mobility and two servos for deploying the solar panel. The complete bill of materials is listed in Table 2, and the schematic diagram is shown in Figure 8.

**Table 2. List of electronic components**

| ITEM | QUANTITY |
|---|---|
| RPLIDAR A1M8 | 1 |
| Embedded Arduino Mega 2560 | 1 |
| HC-06 Bluetooth Module | 1 |
| ESP32-CAM Module | 1 |
| DC Motor | 6 |
| BME280 Sensor | 1 |
| Servo motor | 2 |
| H-Bridge Motor Driver | 3 |
| 1300 mAh Rechargeable Battery | 2 |
| HC-SR04 Ultrasonic Sensor | 1 |
| MLX90614 Infrared Temperature Sensor | 1 |
| MAX4466 Microphone Module | 1 |
| Solar Panel | 2 |

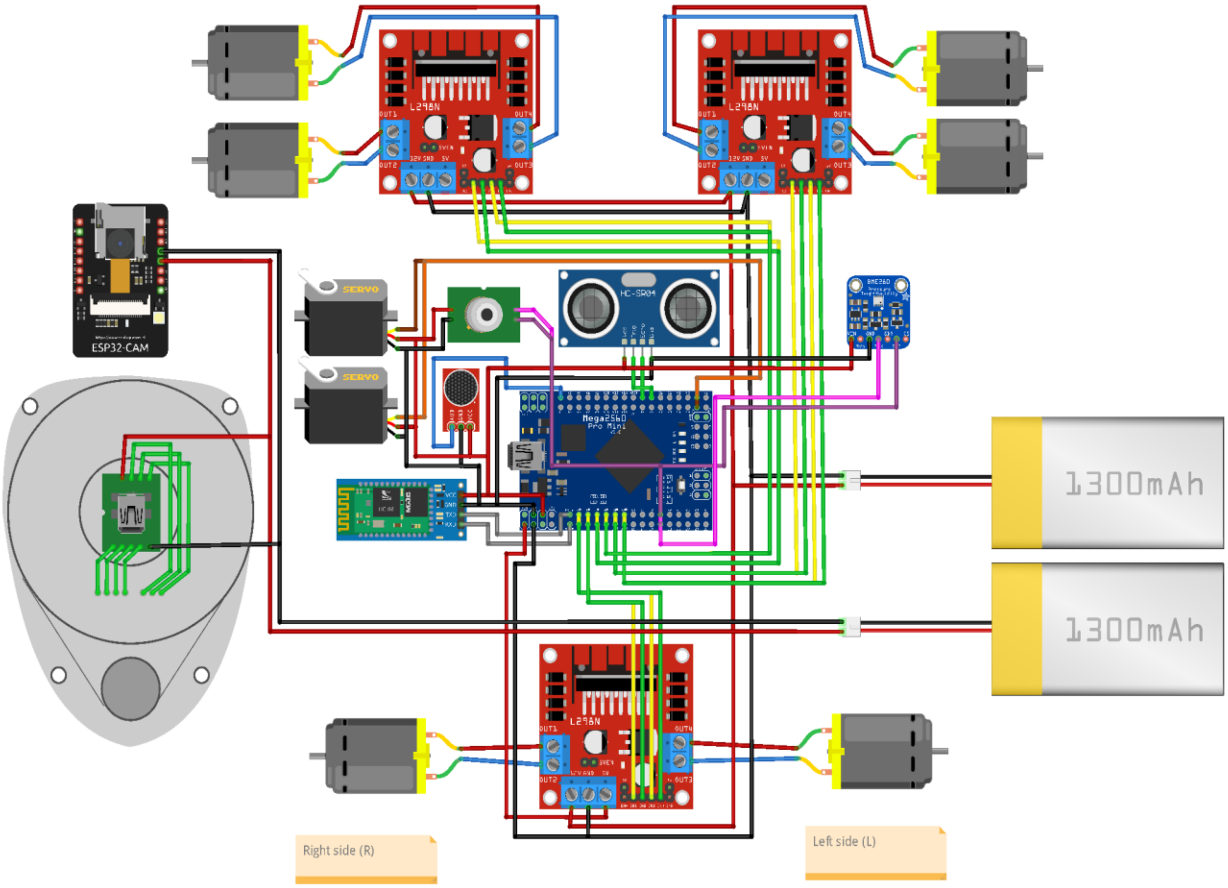


**Fig. 8 Electronic schematic diagram designed in Fritzing**

### *2.3.4. Power System*

The rover has a power system consisting of deployable solar panels and an intelligent battery management system. The panels are mounted on supports located on the sides of the chassis, which remain at rest during normal operation. When a low battery charge level is detected, these panels automatically deploy sideways into a horizontal position to optimize solar energy collection. This deployment can also be activated manually through the control application.

During the battery charging process, the entire system enters a low-power mode in order to optimize functionality. In this state, the microcontroller temporarily disables non-essential modules and registers, thereby reducing energy consumption and shortening the charging time without completely shutting down the system. This configuration allows the rover to resume its operation and functionality more rapidly once the batteries reach an adequate charge level.

## ***2.4. Software and Control System***

### *2.4.1. Autonomous Navigation Stack*

The developed perception system is based on a simple reactive methodology and uses a sensor configuration and arrangement for obstacle detection in unknown environments. The primary sensor used is the RPLIDAR, which generates a two-dimensional point cloud of the surrounding environment within its field of view.

The incoming data is processed by the microcontroller, which analyzes and quantifies distances across a 360-degree field of vision to interpret the environment and identify the presence of obstacles within the sensing area.

Regarding a backup detection unit, an ultrasonic sensor was employed, positioned in the direction of motion. The primary function of this sensor is to reinforce frontal obstacle detection and provide a secondary source of information that enhances the overall reliability of the system, particularly in situations where the primary sensor (LiDAR) may be temporarily affected by environmental conditions in hostile settings, such as reflective surfaces or occasional interference.

When an obstacle is detected within the system’s sensing range, the algorithm is triggered and initiates an evasive maneuver, such as a 90-degree turn to the right or left. Under normal operating conditions, the rover maintains straight-line motion. Although the logic is simple, it provides a minimal level of autonomy, ensuring that the vehicle navigates in a reasonably safe manner without requiring any map or trajectory planning.

### *2.4.2. Remote Control Application*

Wireless communication between electronic systems often presents certain challenges during connection, as it depends on various factors related to the hardware infrastructure itself, such as antenna size and gain, Radio-Frequency (RF) modules, Wi-Fi or Bluetooth interfaces, among others. Connection issues may also arise due to noise, distance, or potential desynchronization. Additionally, proper configuration of the transmitter, receiver, and the data transmission channel is essential.

Furthermore, full duplex communication was implemented to simultaneously send commands and receive telemetry data, since it is necessary to transmit control information to the vehicle while receiving sensor-generated data at the same time.

Controlling an electronic system requires a dedicated control unit to issue operating commands. This control system is usually implemented by another specialized electronic system.

However, it can also be defined by software, which reduces costs related to physical components. Therefore, a software-based remote control system was developed, designed for mobile devices with the Android operating system.

MIT App Inventor was used as the development tool for the mobile application, a visual platform based on blocks that was chosen for its effectiveness in integrating with electronic systems and facilitating the prototyping process, despite its limitations in terms of advanced functionalities.

The design and relative dimensions of each interface element were defined, allowing for an adaptable and resizable design for different mobile devices (see Figure 9). Figure 10 shows a snippet of the block-based code that manages the Bluetooth connection logic, a key element in the communication between the application and the electronic system.

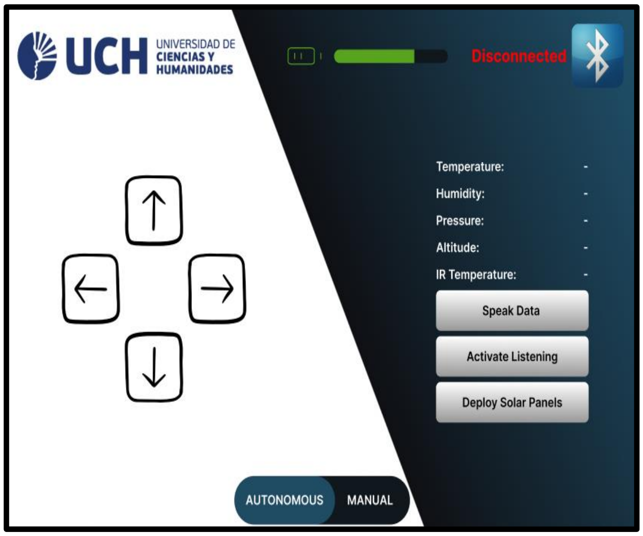
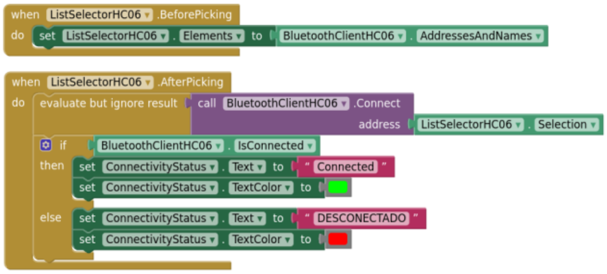


**Fig. 9 Mobile application interface for Android devices, designed in MIT App Inventor**



```
when ListSelectorHC06 .BeforePicking
do  set ListSelectorHC06 . Elements to BluetoothClientHC06 . AddressesAndNames

when ListSelectorHC06 .AfterPicking
do  evaluate but ignore result  call BluetoothClientHC06 .Connect
                                                 address ListSelectorHC06 . Selection
    if   BluetoothClientHC06 . IsConnected
    then set ConnectivityStatus . Text to " Connected "
         set ConnectivityStatus . TextColor to
    else set ConnectivityStatus . Text to " DESCONECTADO "
         set ConnectivityStatus . TextColor to
```

**Fig. 10 Fragment of the block-based logic in MIT App Inventor for establishing the Bluetooth connection**

## *2.5. Experimental Setup and Testing Procedure*

The test protocol was designed to systematically evaluate each of the rover's operating modes and functionality. All tests were conducted with the battery bank charged to over 80% to ensure the proper functioning of all components.

### *2.5.1. Initial Setup and Configuration*

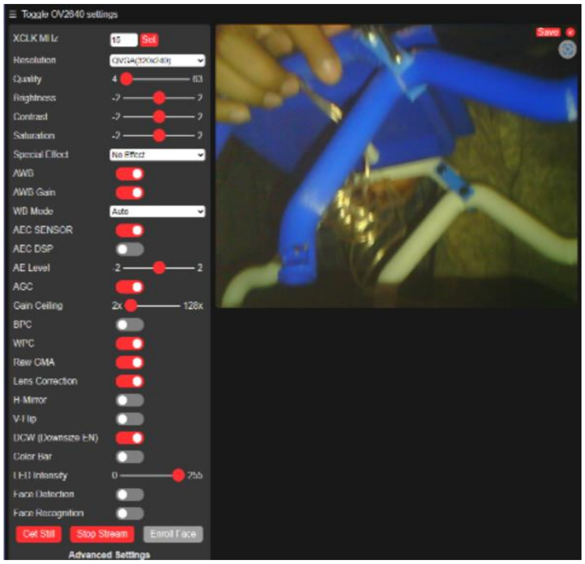
1. The rover was powered on, and a Bluetooth connection was established with the mobile app.
2. The app verified that telemetry data (values from the BME280 and MLX90614 sensors, and battery status) was being received correctly.
3. Video Configuration: Since the ESP32-CAM module operates as a standalone video server, the real-time stream was accessed by entering the module's IP address in an external web browser, as shown in Figure 11, on a device connected to the same Wi-Fi network. This stream was monitored in parallel during testing.

### *2.5.2. Autonomous Mode Testing*

1. A starting point within the testing area was established for the robot and included obstacles that could be no higher than five centimeters.
2. The robot was put into autonomous mode. The RPLIDAR was the primary source of navigation and environmental mapping, while the HC-SR04 ultrasonic sensor had a secondary role for detecting obstacles less than five centimeters; both sensors were used to detect extremely small obstacles ahead of the robot.
3. The Rocker-Bogie suspension system was capable of traversing slopes and obstacles with a height of less than five centimeters; however, due to the weight of the robot and the limited power from the motors, navigating over obstacles with heights of more than five centimeters is difficult for the robot when on low-friction surfaces.
4. One limitation identified is that the robot cannot reliably detect gaps or low-height obstacles. The RPLIDAR is constrained by its sensing plane above the ground, so it cannot perceive features below that level. Although the ultrasonic sensor is mounted closer to the ground, it has a limited field of view and effective range. As a result, any feature that falls outside the detection region of both sensors remains undetected, which can compromise navigation.

### *2.5.3. Manual Mode Tests*

1. The rover operator controlled the rover via the mobile application using a directional button, as in Figure 12.
2. The rover performed command functions immediately, with no detectable latency, within an approximate Bluetooth effective range of 10 meters in the absence of interference. However, when the operator moved beyond this distance, the Bluetooth connection became unstable and was eventually lost.
3. "Speak Data" was correctly established as the application spoke to the user and provided the values for the environmental sensor data.
4. The solar panels were deployed via servomotors, confirming that they are functioning correctly.
5. The microphone module was tested successfully, and the audio from the surrounding environment was broadcast over the application and was audible to the operator.



Toggle OV2640 settings
XCLK MHz 10 Set
Resolution QVGA(320x240)
Quality 4 — 63
Brightness -2 — 2
Contrast -2 — 2
Saturation -2 — 2
Special Effect No Effect
AWB ●
AWB Gain ●
WB Mode Auto
AEC SENSOR ●
AEC DSP ○
AE Level -2 — 2
AGC ●
Gain Ceiling 2x — 128x
BPC ○
WPC ●
Raw GMA ●
Lens Correction ●
H-Mirror ○
V-Flip ○
DCW (Downsize EN) ●
Color Bar ○
LED Intensity 0 — 255
Face Detection ○
Face Recognition ○

**Fig. 11 Video result of ESP32CAM module**

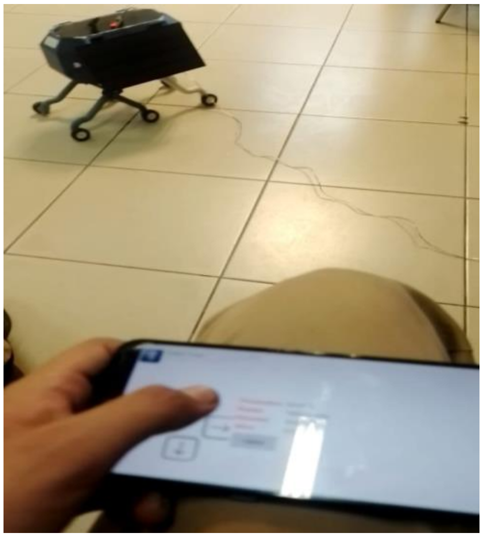


**Fig. 12 Rover manual mode**

## 3. Results and Discussion

### 3.1. Results

The very first tests of the RPLIDAR A1M8 LiDAR sensor occured before any other testing was done. The sensor can produce accurate maps based on scans of the area around the sensor, in near real time (Figure 13). Accuracy measurements suggested that the RPLIDAR A1M8 sensor works out to a maximum of about 10 meters; therefore, working in conjunction with other sensors and equipment, this would be a suitable device for use as autonomous navigation inside confined spaces.

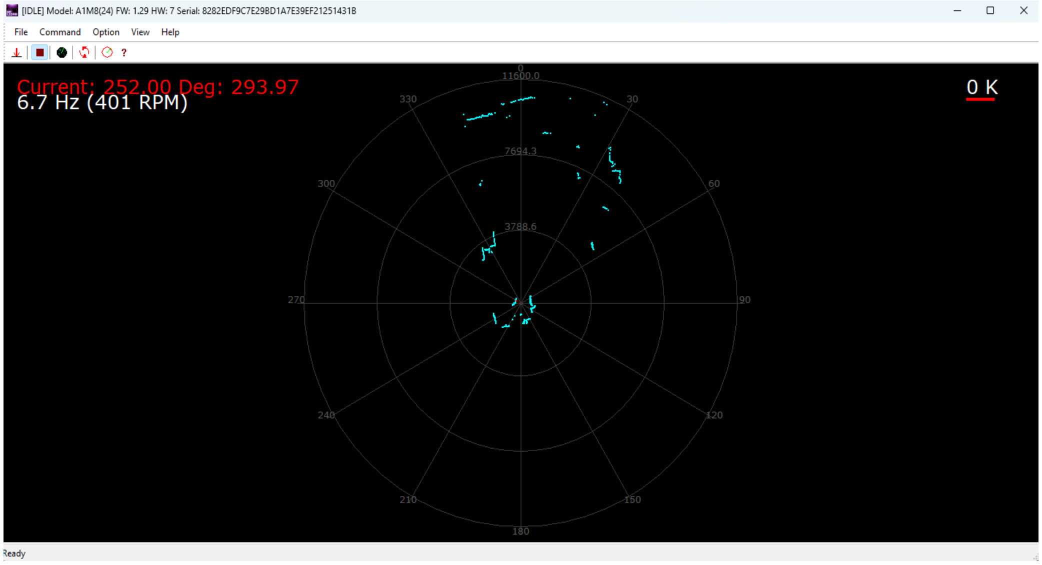


**Fig. 13 Point cloud generated by the RPLIDAR A1M8 during environmental mapping tests**

When combining the perception system with the rocker-bogie suspension of the rover, it provided the capability to autonomously navigate over and avoid obstacles on irregular surfaces; Figure 14 provides validation of this capability. Mobility test results demonstrat ed that the mechanical model of the rover met the established criteria for stability and traction while operating on complex surfaces to execute operations in difficult environments.

**Fig. 14 Rover during mobility tests in autonomous mode**

The UART Serial Port Configuration Error was calculated to evaluate the reliability of the communication link between the ATmega2560 microcontroller and an HC-06 Bluetooth module configured at a baud rate of 9600 bps by calculating the UBRR register using the fosc clock (oscillator) frequency divided by the Baud Rate (9600) in Normal Speed mode.

$$UBRR = \left(\frac{fosc}{16 \times Baud\ Rate}\right) - 1$$

$$UBRR = \left(\frac{16\ 000\ 000}{16 \times 9600}\right) - 1 = 103.17$$

Since UBRR must be an integer, it was rounded to 103. With this value, the resulting actual baud rate is:

$$Baud\ Rate\ Real = \left(\frac{fosc}{16 \times (UBRR+1)}\right)$$

$$Baud\ Rate\ Real = \left(\frac{16\ 000\ 000}{16 \times 104}\right) = 9615.38\ bps$$

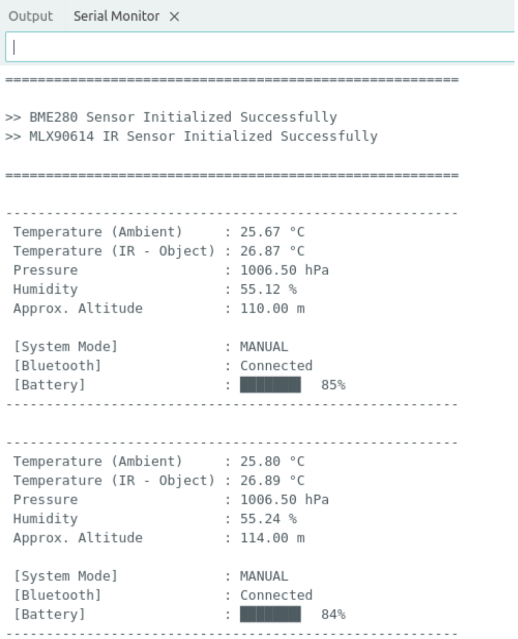
Error percentage,

$$Error\ \% = \left(\frac{|Baud\ Rate\ Target - Baud\ Rate\ Real|}{Baud\ Rate\ Target}\right) \times 100$$

$$Error\ \% = \left(\frac{|9600 - 9615.38|}{9600}\right) \times 100 \approx 0.16\%$$

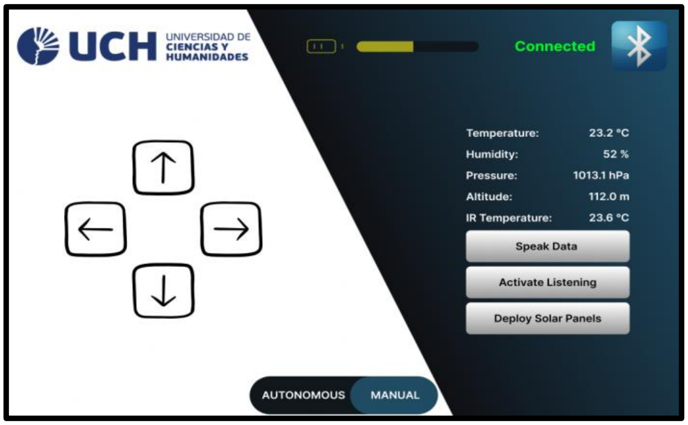
A 16 MHz crystal produces a calculated value for 9600 baud with a 0.16 % error, which falls within the manufacturer's specification for reliable and stable serial communication. Sensor functionality was also assessed; sensors capable of measuring temperature, atmospheric pressure, relative humidity, and altitude reliably capturing and displaying time-sensitive environmental data (See Figure 15). These sensors provide an accurate and reliable source of environmental data, which is essential to the successful operation of rovers during exploration missions.

Lastly, the performance of the HC-06 Bluetooth communication module was verified in terms of the ability to transmit information remotely and in real time, thereby providing a stable and continuous communication link during rover operations (See Figure 16).



```
========================================================

>> BME280 Sensor Initialized Successfully
>> MLX90614 IR Sensor Initialized Successfully

========================================================

--------------------------------------------------------
 Temperature (Ambient)     : 25.67 °C
 Temperature (IR - Object) : 26.87 °C
 Pressure                  : 1006.50 hPa
 Humidity                  : 55.12 %
 Approx. Altitude          : 110.00 m

 [System Mode]             : MANUAL
 [Bluetooth]               : Connected
 [Battery]                 : ██████   85%
--------------------------------------------------------

--------------------------------------------------------
 Temperature (Ambient)     : 25.80 °C
 Temperature (IR - Object) : 26.89 °C
 Pressure                  : 1006.50 hPa
 Humidity                  : 55.24 %
 Approx. Altitude          : 114.00 m

 [System Mode]             : MANUAL
 [Bluetooth]               : Connected
 [Battery]                 : ██████   84%
--------------------------------------------------------
```

**Fig. 15 Sensor readings and system status on the serial monitor**



Temperature: 23.2 °C
Humidity: 52 %
Pressure: 1013.1 hPa
Altitude: 112.0 m
IR Temperature: 23.6 °C

**Fig. 16 System in operation: mobile application connected to the rover and displaying real-time sensor data acquisition**

Furthermore, verification was performed on the ESP32-CAM camera module that is used for both image capturing and real-time video streaming. The camera was found to function appropriately and reliably during the test phase, providing a stream to a web browser through the correct IP address (as shown in Figure 17). As real-time viewing is essential to conduct exploration and rescue operations, an operator has access to direct visual information regarding their environment. Although this design feature was successful, the absence of integrating the ability to view video from within the primary mobile application added to the` operation's complexity. Improvements could be made to deliver an overall better user experience and operational effectiveness. Finally, 1000 samples were collected from the environmental sensors to verify their stability and accuracy, the results of which are presented in Figure 18.

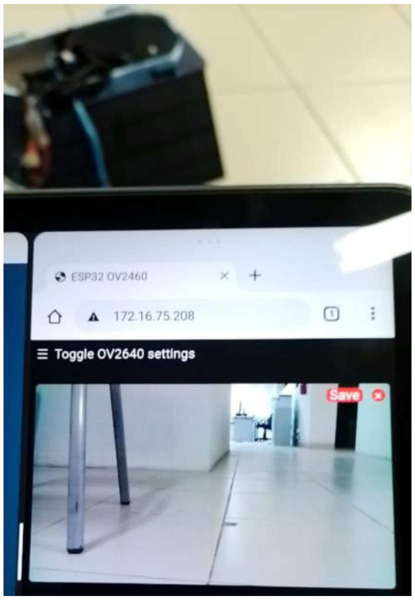


Fig. 17 Streaming video from the ESP32-CAM in a web browser

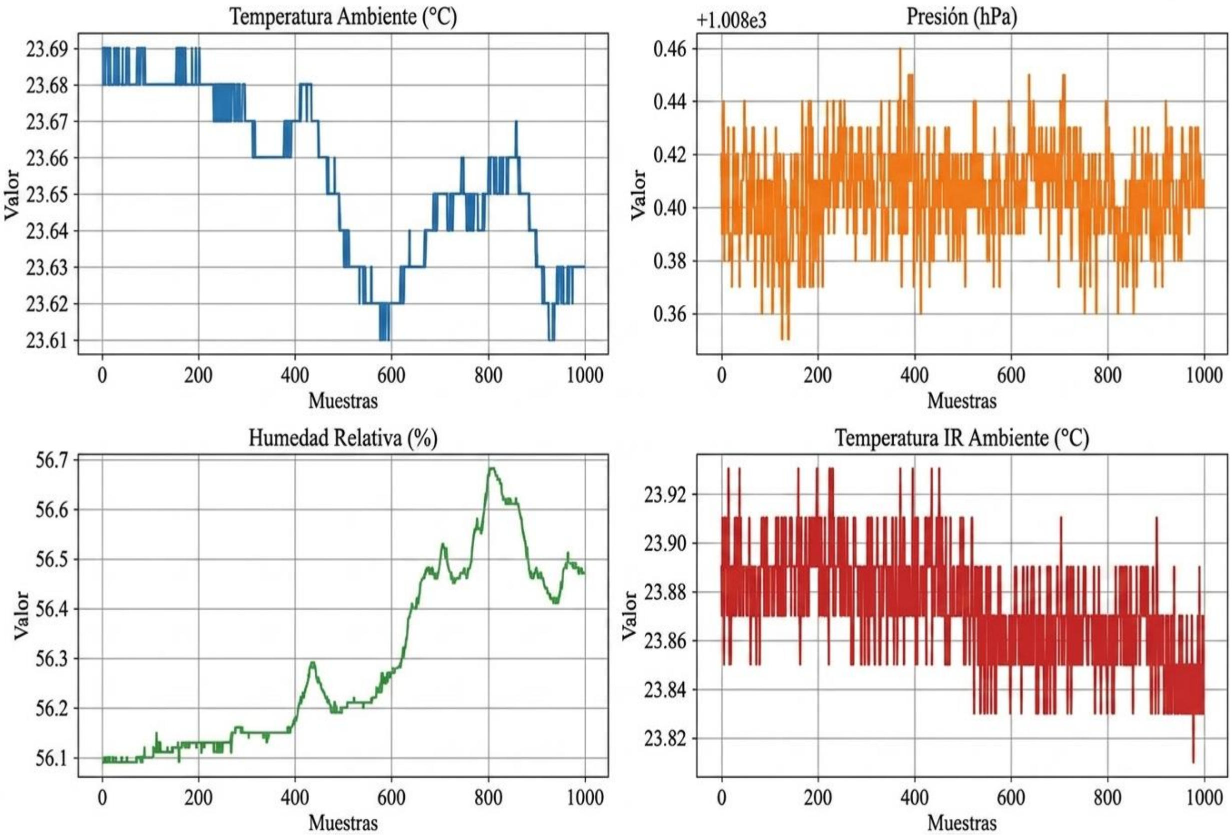


Fig. 18 Environmental sensor readings: Temperature, pressure, humidity, and infrared data over 1000 samples

### *3.2. Discussion*

The development and evaluation of the robotic prototype demonstrate its technical feasibility for Search and Rescue (SAR) missions in complex environments. In terms of connectivity, the stability observed using the HC-06 Bluetooth module is consistent with low-cost microcontroller-based architectures for short-range missions [14]. However, for operations requiring extensive environmental monitoring, the literature suggests transitioning toward more robust networking protocols such as ZigBee to improve the transmission of critical data [15].

Navigation in unstructured environments revealed that, although the RPLIDAR sensor enables real-time characterization through point clouds, as shown in Figure 13, mapping accuracy depends on sensor validation against environmental noise [16]. Compared with advanced Simultaneous Localization and Mapping (SLAM) algorithms implemented on collaborative robotic platforms [17], our system requires deeper odometry integration to prevent drift along the Z-axis, a challenge documented in 3D navigation using optimal RRT* planners in indoor incidents [18]. Furthermore, operational versatility could be enhanced through the use of multi-modal coaxial platforms capable of adapting to diverse terrain profiles [19].

Regarding mechanical performance, the rocker-bogie system (Figure 14) validated its static load distribution capability for overcoming irregular obstacles [20]. To maximize exploration coverage in highly uneven terrains, one study proposes that robot collaboration-where one platform acts as a bridge or ramp for another-is a superior strategy compared to individual autonomy [21]. This traction capability is further enhanced by the kinematics of the design [22], although torque limitations suggest the incorporation of posable hub mechanisms to optimize chassis leveling on extreme slopes [23]. The operator’s situational awareness was strengthened through the integration of environmental sensors and real-time visual transmission. Figure 15 demonstrates the continuous acquisition of temperature, pressure, humidity, and infrared detection data through the serial monitor, while Figure 16 shows the remote visualization of these parameters through a mobile application connected to the rover. Additionally, the real-time video transmission from the ESP32-CAM to a web browser (Figure 17) complemented the operational perception of the environment, enabling the supervision of potentially hazardous conditions without direct operator exposure. These results are consistent with environmental monitoring approaches in SAR robots reported in the literature [24]. However, the tests also revealed integration challenges and wireless communication range limitations, suggesting the need for more robust communication protocols and advanced teleoperation interfaces with haptic feedback to reduce cognitive workload during operations in real disaster scenarios [25]. These operational lessons are essential for bridging the gap between laboratory prototypes and real-world deployments documented by rescue robotics centers [26]. The robustness of these systems can be evaluated through multi-sensor datasets covering diverse platforms and motion patterns, ensuring SLAM algorithm generalization [27].

Finally, future work will focus on implementing integrated deep learning frameworks such as YOLOv8 for optimized victim detection [28]. Likewise, system scalability will depend on the formation of swarm alliances using coordinated frontier exploration algorithms [29]. To ensure the integrity of these multi-robot networks, it is imperative to integrate cloud-based computation management and security systems capable of mitigating intrusion risks during critical missions [30].

## 4. Conclusion

In this study, we designed, built, and validated a prototype mini-rover for exploratory and rescue operations. The mini-rover integrated successfully both in autonomous and manual modes with a rocker-bogie suspension system and an array of sensors that monitored the environment and provided data to enable navigation.

Some of the key accomplishments include developing a viable functional prototype that has fulfilled the majority of its primary specifications. The autonomous navigation stack, utilizing a reactive algorithm with RPLIDAR and ultrasonic sensor data, successfully demonstrated simple obstacle avoidance behaviour. The mobile app provided effective real-time telemetry, voice feedback, and remote control through Bluetooth that was highly stable (0.16% error rate) when using the UART configuration. In addition to these activities, the solar charging system and the mechanical design were both reliable for operation on rugged terrain. During the testing of the robot, there were a few limitations; The operating range was limited to just over 10 meters due to the limitations of the HC-06 Bluetooth module. Furthermore, the DC motors lacked sufficient torque to consistently overcome obstacles larger than 5 cm, and the main application did not natively integrate video to allow users to access the ESP 32-CAM’s video signal. Instead, access was via IP through a web browser, which contributed to the robot’s inefficiency and reduced its operational effectiveness in terms of range and obstacle-overcoming capabilities.

Several enhancements to increase the functionality of the developed system are suggested for future work, including the addition of long-range communication protocols like Wi-Fi or LoRa to allow the robot(s) to function in real-world search and rescue environments that are greater than 100 meters away. All drive systems will be upgraded to use higher torque DC or stepper motors, with encoders added for improved speed and positional control. The wheels are proposed to be redesigned with either treads or spikes for better traction in loose or slippery terrain; furthermore, the creation of a fully integrated user interface, including a video stream utilizing protocols such as RTSP, will enhance usability and situational awareness for the operator. Finally, further exploration of advanced navigation algorithms such as Simultaneous Localization and Mapping (SLAM) is anticipated to allow for autonomous exploration of completely unknown environments. While this work has limitations in its current state, it provides solid proof of concept and represents a good starting point for the future development of low-cost search and rescue robots.

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