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Original Article

Vision and communication system prototype for search and rescue applications in collapse scenarios

Prototipo de sistema de visión y comunicación para aplicaciones de búsqueda y rescate en escenarios de derrumbe

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Spanish version

Abstract

Introduction: This paper presents the development and implementation of a low-cost wireless vision and communication system prototype, designed to be integrated into mobile exploration platforms for collapse scenarios. In these situations, search teams require immediate visual information and telemetry without exposing themselves to secondary risks in hard-to-reach areas.
Objective: To implement a low-cost video acquisition and bidirectional data transmission system for victim localization and environmental assessment.
Methodology: The prototype development was structured using the V Model approach, utilizing traceability matrices and Pugh matrices for component selection. A dual microcontroller architecture communicating via an I²C bus was implemented to solve the camera physical port constraints.
Results: A functional prototype was successfully developed with stable video transmission over distances up to 90 m. The lighting modes showed versatility for dark environments, while the displacement platform responded adequately on ramps up to 30°under controlled conditions, although difficulties were observed when climbing smooth obstacles.
Conclusions: The experimental results suggest the preliminary technical feasibility of the evaluated electronic and logic architecture, indicating that it represents a feasible low-cost architecture for data acquisition and video streaming. However, the limitations observed in the traction of the tracks and the dimensions of the chassis constitute clear physical boundaries of the current design that restrict its immediate use in real disaster scenarios.

Keywords: Disasters, Robotics, Embedded systems, Telecommunication, Rescue work, Remotely operated vehicles

Resumen

Introducción: Este artículo presenta el desarrollo e implementación de un prototipo de sistema inalámbrico de visión y comunicación de bajo costo, diseñado para integrarse en plataformas móviles de exploración en escenarios de colapso. En estas situaciones, los equipos de búsqueda requieren información visual y telemetría inmediatas sin exponerse a riesgos secundarios en áreas de difícil acceso.
Objetivo: Implementar un sistema de adquisición de video y transmisión bidireccional de datos de bajo costo para la localización de víctimas y la evaluación ambiental.
Metodología: El desarrollo del prototipo se estructuró utilizando el modelo V, empleando matrices de trazabilidad y matrices de Pugh para la selección de componentes. Se implementó una arquitectura de microcontrolador dual que se comunica mediante un bus I²C para resolver las limitaciones del puerto físico de la cámara.
Resultados: Se desarrolló con éxito un prototipo funcional con transmisión de video estable a distancias de hasta 90 m. Los modos de iluminación demostraron versatilidad en entornos oscuros, mientras que la plataforma de desplazamiento respondió adecuadamente en rampas de hasta 30° en condiciones controladas, aunque se observaron dificultades al superar obstáculos lisos.
Conclusiones: Los resultados experimentales sugieren la viabilidad técnica preliminar de la arquitectura electrónica y lógica evaluada, lo que indica que representa una arquitectura viable y de bajo costo para la adquisición de datos y la transmisión de video. Sin embargo, las limitaciones observadas en la tracción de las orugas y las dimensiones del chasis constituyen límites físicos claros del diseño actual que restringen su uso inmediato en escenarios reales de desastre.

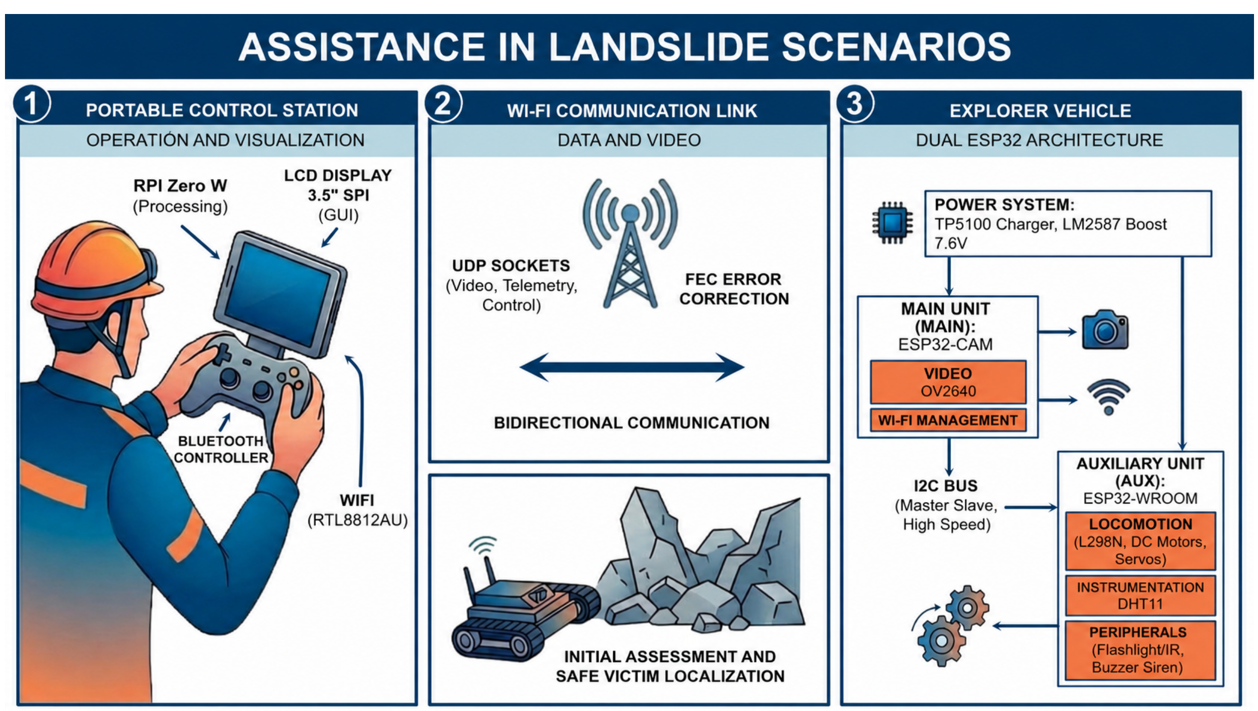
Palabras clave: Desastres, Robótica, Sistemas embebidos, Telecomunicaciones, Labores de rescate, Vehículos operados a distancia

Why was the study conducted?
The study was conducted to address the safety risks faced by search and rescue teams during the initial assessment of collapsed structures. Traditional exploration methods often require rescue personnel and animals to enter unstable environments, increasing their exposure to secondary hazards. Although advanced robotic systems have been proposed, their high financial and computational costs limit their adoption, particularly in developing countries. Therefore, this study aimed to design, implement, and evaluate a low-cost, modular wireless vision and telemetry prototype based on commercially available off-the-shelf components.

What were the key findings?
The prototype evaluation showed that the proposed dual-microcontroller architecture successfully addressed the hardware constraints associated with the vision subsystem while providing stable video streaming over distances of up to 90 m under controlled conditions. The hybrid lighting system revealed complementary operating characteristics: the visible LED flash preserved color fidelity at short distances with lower power consumption, whereas the infrared illuminator improved scene visibility in complete darkness at the expense of higher current consumption. Finally, locomotion tests identified clear mechanical limitations, as the 3D-printed PLA tracks achieved a 70% success rate on 30° inclines but exhibited limited traction on smooth and cylindrical obstacles.

What do these findings contribute?
These findings support the preliminary technical feasibility of a low-cost distributed electronic and software architecture for search and rescue exploration. By establishing quantitative baseline performance metrics—including wireless communication range, video transmission latency, power consumption, and locomotion performance—the study provides a practical reference framework for future developments. This framework may support the design of modular, low-cost sensory assistance tools intended for the preliminary inspection of confined spaces while helping reduce the exposure of rescue personnel to secondary hazards.

Graphical Abstract



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Introduction

After a structure collapses, rescue teams face a critical problem: the lack of a safe and fast method to conduct an initial assessment of the scene. The first hours following a disaster are crucial for the survival of victims, demanding an immediate response (1). However, traditional search procedures, which rely on human visual inspection, acoustic sensors, thermal cameras, and rescue dogs, have limitations. Although search dogs are effective thanks to their keen sense of smell, and acoustic systems allow for the location of survivors under the rubble, these methods require the physical entry of personnel and animals into highly unstable areas (2) (3). This direct exposure subjects teams to dangers such as secondary collapses, extreme temperatures, and the presence of toxic gases, which not only puts their safety at serious risk but also delays strategic decision-making due to the lack of prior visual information (4) (5).

The characteristics of collapse scenarios impose restrictions on any exploration operation. Literature defines these environments by the presence of three-dimensional obstacles of various sizes, surfaces with irregular slopes, and steps that hinder progress. Physical access is often restricted by cracks and confined spaces that require reduced entry profiles, typically limited to a few tens of centimeters in width (6) (7). Additionally, the presence of external agents such as suspended dust, loose debris, and stagnant liquids degrades mechanical components, while the total absence of natural light makes the use of active lighting essential (5).

Given the insufficiency of traditional methods in these adverse conditions, search and rescue robotics has evolved to offer various technological alternatives (8). In terms of locomotion, developments range from snake-like articulated systems, designed specifically to penetrate and navigate through narrow cracks and pipes (7) (9), to platforms based on wheels and tracks, such as rocker bogie mechanisms or differential drive chassis, which distribute weight and maximize grip to overcome irregular terrain and stairs (10) (11).

In the field of victim detection and scene assessment, recent research employs advanced computer vision technologies. Algorithmic solutions based on convolutional neural networks, such as YOLOv7 and panoptic segmentation architectures, allow for the analysis of the scene in real time and the identification of survivors from video streams (12) (11). In parallel, communication and teleoperation approaches range from simultaneous mapping and localization (4), to long distance control systems that use GSM and DTMF protocols to operate in remote areas lacking network infrastructure (13). Likewise, the use of cross-platform systems and the Internet of Things has facilitated the transmission of telemetry to commercial mobile devices (14)-17).

In the context of developing countries like Colombia, although there are robotic projects focused on exploration such as the "Thunder" platform (18), the high computational and financial cost of advanced autonomous systems limits their adoption. There is a need for robust, modular, low-cost tools that can be rapidly deployed, using accessible commercial components (16) (19).

To address these operational needs, this work proposes a set of requirements aimed at evaluating the technical feasibility and preliminary performance of the proposed prototype. At a functional level, the architecture seeks to facilitate the acquisition and transmission of a video stream with reduced latency to a portable control station, incorporating active lighting elements to improve

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visibility in scenarios with low-light restrictions. Furthermore, the system aims to establish a bidirectional wireless link and monitor environmental variables. Regarding nonfunctional requirements, the design is oriented towards the use of low-cost components and limited processing times so as not to significantly compromise the fluidity of remote operation.

To evaluate performance in relation to these parameters, the methodology focuses on the analysis of quantitative metrics that provide data on the behavior of the data link, the range of the wireless signal, and the estimated latency of the vision system under the specific conditions of the controlled environment. In this context, the physical ground robotic platform acts as a basic mobile platform.

The limitations of traction and maneuverability of the mechanical chassis before surfaces with high irregularity are recognized, aspects that are defined as boundaries of the current design and constitute areas of improvement for future developments; this methodological limitation allows the study to focus on the feasibility of the electronic and communications architecture. Thus, the work presents the evaluation of a low-cost tool conceived as a possible sensory support option for emergency teams, aimed at improving the collection of initial information and contributing to the reduction of the direct exposure of personnel in the early stages of reconnaissance.

Methodology

The development of the prototype was structured using the V Model (Figure 1). This approach is highly suitable for robotics projects, as it provides a framework for the co-design of hardware and software, ensuring that every conceptual stage is linked to a corresponding evaluation phase.

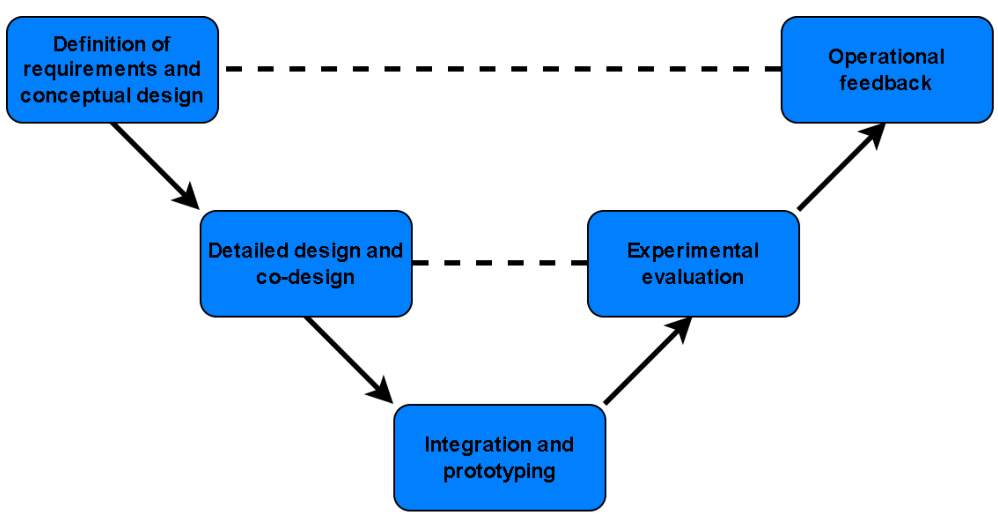

Figure 1. V-model methodology used in this work (Source: Authors)

Following this methodology, the development workflow was executed in the following sequence:

Requirement definition and conceptual design

Based on the operational constraints documented in rescue scenario literature, the initial technical requirements for the system were defined. These included portability, visual capture under low light conditions, telemetry transmission, and cost-effectiveness. Based on these parameters, commercially

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available components for processing, power management, and wireless communication were evaluated and selected.

Detailed design and co-design

A dual electronic architecture was outlined to distribute the processing load between two microcontrollers. In parallel, the software architecture was structured, covering the development of C++ firmware for peripheral control and the programming of the interface for the portable station based on the Raspberry Pi OS environment.

Integration and prototyping

This stage constituted the core of the development process and involved the physical assembly of the electronic subsystems onto a tracked chassis. Furthermore, the communication logic for the internal bus and the bidirectional network link was unified, consolidating the first operational version of the equipment.

Experimental evaluation and feedback

Functional tests were performed in a controlled environment to examine the performance of the integrated system against the initial specifications. Observations obtained during these experiments, such as the slippage of plastic tracks when interacting with inclines or smooth surfaces, allowed for the practical documentation of the design's current operational limits. These preliminary results serve as a reference to suggest specific adjustments in traction and weight distribution for future versions of the prototype.

To structure the development consistently with the principles of the V Model, a traceability matrix was incorporated. This tool links the initial design considerations with the selected components and the testing methods intended to evaluate the overall system performance. Table 1 describes this correspondence.

Table 1. Traceability matrix between Requirements, Selection and Validation of the System (Source: Authors)

Design Requirement	Requirement Type	Selected Component or Design Solution	Experimental Validation Method
Video stream acquisition and remote teleoperation	Functional	ESP32-CAM processing module with RTL8812AU antenna and decoding via libjpeg-turbo library	Measurement of estimated rendering latency and bandwidth consumption
Visual exploration in low-light environments	Functional	Front LED flash for visible light and infrared illuminator managed by the auxiliary ESP32 unit	Image capture tests in the absence of natural light

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Acquisition and visualization of environmental telemetry	Functional	DHT11 temperature and humidity sensor and graphical environment structured in the ImGui library	Verification of variable readings on the statistics panel
Establishment of a bidirectional wireless link	Non-Functional	Wi-Fi protocol in access point configuration using the RTL8812AU adapter	Logging of received signal strength at different distances
Economic viability and use of commercial components	Non-Functional	ESP32 series microcontrollers with Raspberry Pi Zero	Comparative analysis and selection of alternatives using Pugh decision matrices
Basic movement on surfaces with slopes or obstacles	Functional	Crawler traction chassis (Rover Tracks v2) controlled by DC motors	Transit tests on ramps and over cylindrical profiles in a controlled environment

Comparison of Design Alternatives

The following sections present various alternatives that satisfy the project’s electronic needs.

Table 2 provides a detailed comparison of the most commonly used microcontrollers on the market.

Table 2. Microcontrollers comparison (Source: Authors)

Specifications	**Microcontrollers**				
Model	**ATMEGA328P**	**PIC16F877**	**ESP8266**	**Raspberry Pi Pico**	**ESP32**
Development boards with integrated cameras	NO	NO	NO	NO	YES
Wi-Fi	NO	NO	YES	YES	YES
Dual core	NO	NO	NO	YES	YES
Current Consumption (mA)	27	25	67	80	80

Likewise, Table 3 shows a comparison between the different H-bridge candidates to drive the vehicle motors.

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Table 3. H-bridge comparison (Source: Authors)

Specifications	H-bridge		
Model	L298N	L9110S	L293D
Max current (A)	2	0.8	0.6
Channels	2	2	2
Input voltage range (V)	5 - 35	2.5 - 12	5 - 35

Similarly, Table 4 displays the comparison between alternative embedded systems that could be used for the operator control system.

Table 4. Embedded systems comparison (Source: Authors)

Specifications	Embedded systems			
Model	Raspberry Pi 4 model B	Raspberry Pi 1 model B	Raspberry Pi zero w	Orange Pi zero 2w
Dimensions (mm)	85x56	85x56	65x30	65x30
CPU Cores	Quad-core	Single-core	Single-core	Quad-core
Current Consumption (mA)	900	550	250	350

However, comparisons alone do not provide enough of a basis for making decisions regarding which alternatives to use. Therefore, the selection of components for the system design and operator control is carried out using Pugh matrices.

Selection of Design Alternatives

The Pugh tables presented below simplify the objective selection of components by comparing them against a reference point, which will be the most popular component. If the compared component provides greater benefits, it is assigned a plus sign (+); otherwise, it is assigned a minus sign (-). If the comparison results in equality with the reference, it is assigned an equals sign (=). Positive signs add 1 to the total count, negative signs subtract 1, and equal signs add zero.

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Table 5. Pugh matrix of microcontrollers (Source: Authors)

Microcontrollers					
Feature	**Alternatives**				
	ATMEGA328P	**PIC16F877**	**ESP8266**	**Raspberry Pi Pico**	**ESP32**
	REF	=	=	=	+
Wi-Fi	REF	=	+	+	+
Dual core	REF	=	=	+	+
Current	REF	+	-	-	-
Total		**1**	**0**	**1**	**2**

After analyzing the results for the microcontrollers in Table 5, the ESP32 was determined to be the most suitable option for the project. This choice is supported by its ability to meet various vehicle needs, including the availability of development boards that integrate it with cameras like the OV2640, such as the ESP32-CAM, whose images are processed by utilizing the large number of I/O pins of the microcontroller. Additionally, it facilitates video transmission through its integrated Wi-Fi connection.

Table 6. Pugh matrix of H-bridges (Source: Authors)

H-bridge			
Feature	**Alternatives**		
	L298N	**L9110S**	**L293D**
Max current (A)	REF	-	-
Channels	REF	=	=
Input voltage range (V)	REF	-	=
Total		-2	-1

Regarding Table 6, the selection of the most suitable H-bridge was selected as the L298N, thanks to its ability to control motors with a current and voltage consumption of up to 2 amperes and 35 volts.

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Table 7. Pugh matrix of Embedded systems (Source: Authors)

Embedded systems				
Feature	**Alternatives**			
	Raspberry Pi 4 model B	**Raspberry Pi 1 model B**	**Raspberry Pi zero w**	**Orange Pi zero 2w**
Dimensions (mm)	REF	=	+	+
CPU Cores	REF	-	-	=
Current	REF	+	+	+
Total		**0**	**1**	**2**

Based on the data provided in Table 7, which corresponds to the selection of the embedded system for the operator control station, the Orange Pi offers the best technical features. However, considering that the control system must be portable for easy deployment in the field and powered by batteries, the low consumption of the Raspberry Pi Zero W stands out. Furthermore, despite having fewer cores, its work is limited to receiving data and video from the vehicle and sending control commands, which does not require significant processing power, making it the most suitable option for this project.

The sensors to be used on the vehicle depend on the context in which it is used. For this reason, the DHT11 temperature and relative humidity sensor will be used as an example; however, any sensor compatible with the GPIO pins of the microcontroller and its interfaces could be implemented.

For image visualization on the control station, a small 3.5-inch SPI LCD screen compatible with the pin header of the chosen embedded system will be used to ensure portability.

Transmission distance is crucial. However, since the transmission is performed via Wi-Fi, any standard Wi-Fi adapter will allow for a maximum transmission power of 20 dBm. As an example, an adapter based on the RTL8812AU chip will be used.

Dual Microcontroller Integration

The control system implementation was based on a dual microcontroller architecture to address a critical physical constraint of the vision hardware, as shown in the communication block diagram (Figure 2).

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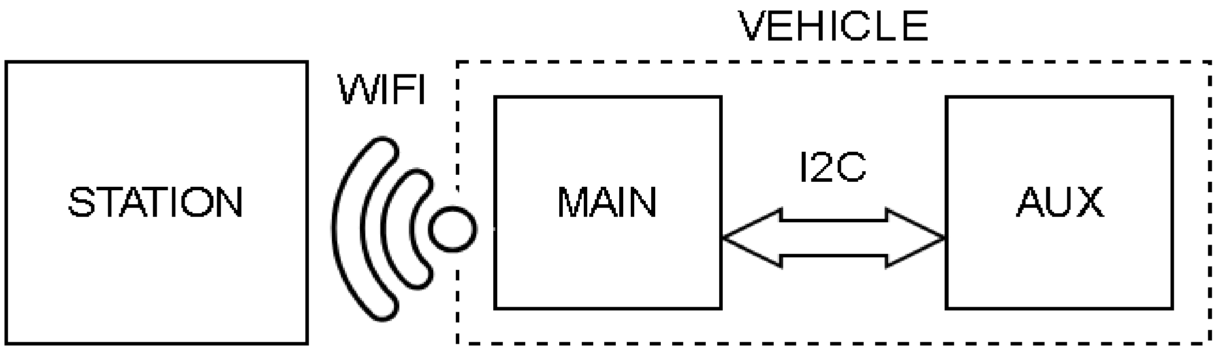

Figure 2. Communication block diagram (Source: Authors)

Although the ESP32-CAM module ("Main") possesses sufficient processing power for concurrent tasks, the data bus and control signals of the OV2640 camera occupy most of its GPIO pins, preventing direct actuator management. To overcome this, an ESP32 WROOM was integrated as an auxiliary unit ("Aux"). As detailed in the electronic schematic (Figure 3), this unit functions as an intelligent port expander responsible for the direct control of electromechanical elements and sensors.

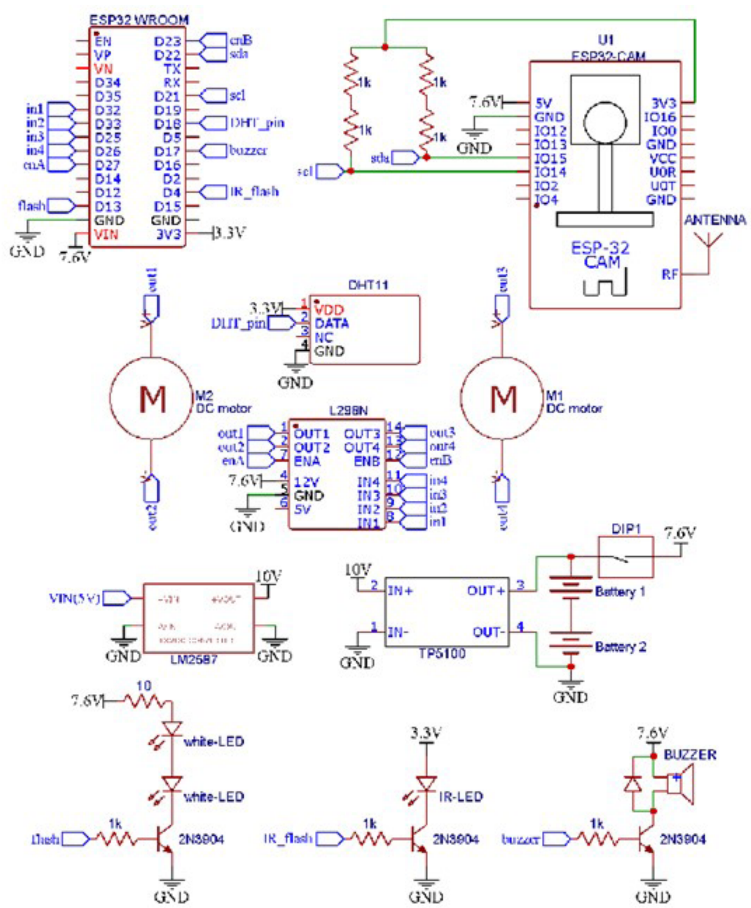

Figure 3. Vehicle Schematic (Source: Authors)

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Communication between both units was established via the I²C bus, selected for its high transfer speed and minimal header overhead, which are key factors in ensuring imperceptible latency during teleoperation. Under this configuration, the Main unit handles the Wi-Fi link with the base station and video capture, while the Aux unit executes logic signals to the H-bridge and manages navigation peripherals, including a front LED flash, an infrared emitter for night vision, and a passive buzzer for acoustic alerts.

Power System and Management

The power system design was based on a theoretical estimation of the active components' nominal consumption, aiming for a target autonomy of approximately 10 hours for the control station and over 3 hours for the exploration vehicle.

For the control station, the DC power demand was calculated by summing the nominal consumption of its main modules: the Raspberry Pi Zero W processing unit (250 mA), the 3.5-inch LCD screen (150 mA), and the RTL8812AU wireless network adapter (100 mA). This initial analysis yielded a continuous theoretical consumption of 500 mA. To meet the autonomy goal under this demand, a parallel array of two lithium-ion cells with a capacity of 2200 mAh each was selected, totaling 4400 mAh. Relating this capacity to the estimated current, an approximate operating time of 8.8 hours was projected.

Regarding the vehicle, the energy source design was constrained by both the estimated electrical demand and the physical space restrictions within the chassis. The theoretical consumption for the mobile platform was derived from its active subsystems: the ESP32 dual microcontroller architecture (80 mA per unit, totaling 160 mA), two DC motors under average traction conditions (200 mA per motor, totaling 400 mA), the test telemetry sensor (<5 mA), and the active infrared lighting module (300 mA). This represents a continuous demand of approximately 565 mA during standard transit without active lighting, and a maximum estimated consumption of 865 mA when operating all peripherals simultaneously.

Because the volume inside the chassis limited the size and quantity of the cells, a compact series configuration of two lithium cells with a 3000 mAh capacity and 7.6 V was chosen. Under the maximum calculated theoretical demand, this configuration offers an expected operation time of 3.47 hours.

To verify these theoretical estimates, direct current measurements were performed by opening the circuit and connecting an ammeter in series. In the control station, measurements showed a current draw of 440 mA at peak activity, close to the 500-mA theoretical projection. In the vehicle, measurements recorded a demand of 240 mA with the camera active in idle mode. Upon activating the visible light flash, the value rose to 315 mA; with the infrared emitter, consumption reached 550 mA; and with the acoustic alert buzzer, it reached 330 mA. During basic movement with active video streaming, the measured consumption was 860 mA, while operating movement simultaneously with all lighting and alert peripherals reached a maximum of 1.3 A.

To facilitate recharging using standard 5 V sources, the vehicle incorporates a TP5100 series charging module assisted by an LM2587 voltage booster, which steps up the input voltage to the

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10 V required by the charger. The control station power management relies on a TP4056 module, optimizing discharge by utilizing the low dropout regulator (LDO) integrated into the Raspberry Pi Zero W. This regulator allows the station to maintain stable operation with an input voltage as low as 3.5 V, enabling efficient use of the battery throughout almost its entire discharge cycle without requiring additional voltage boosting stages that introduce losses.

Mechanical Locomotion and Structural Design

Mobility in environments characterized by rubble and irregular surfaces was addressed through a crawler track system (Figure 4-A), which is ideal for distributing weight evenly and maximizing traction on unstable terrain (20). Control of the DC motors was achieved via an L298N H-bridge, which received pulse width modulation (PWM) signals from the Aux unit to precisely regulate both direction and speed.

The mechanical design and protective chassis were manufactured using 3D printing, based on adapted open-source models under a Creative Commons Attribution (CC BY) license. Specifically, the "Rover Tracks v2" traction system (Figure 4-A) (21) and a modified version of the "ZeroBot Pro Tank" chassis (Figure 4-B) (22), were integrated, resulting in a compact and robust structure capable of protecting the internal electronics during exploration, as shown in the final assembly (Figure 4-C and Figure 4-D).

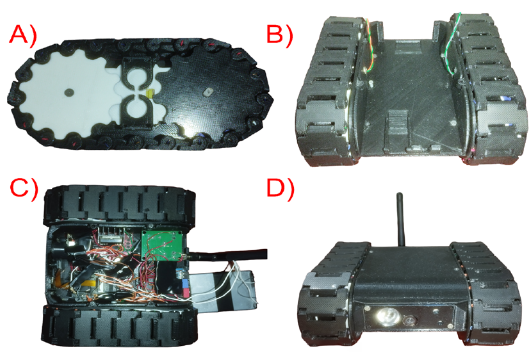

Figure 4. A) Tracks B) Chassis C) Vehicle Interior D) Final Assembly (Source: Authors)

Control Station and Telemetry

The remote-control system, named "Station," was conceived as a portable and autonomous unit, prioritizing ergonomics and energy efficiency. To integrate the components (Raspberry Pi Zero W, battery, screen, and antenna) into a single handheld unit, a structural support was 3D printed based on an open-source model under a CC BY license (Figure 5) (23). This assembly was coupled with a Bluetooth controller, providing an interface for real-time telemetry.

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Figure 5. Station (Source: Authors)

Electronically, component integration required custom solutions to ensure operational stability, detailed in the station schematic (Figure 6). Since the system lacked a stable 5 V line, a manual bypass of the 3.5-inch LCD screen's internal AMS1117 regulator was performed to power it directly from the 3.3 V rail of the Raspberry Pi. Similarly, wireless communication was handled by a Wi-Fi adapter based on the RTL8812AU chip; for a compact integration, the differential data lines were soldered directly to the test pads of the processor's USB port, showing stable operation at the nominal battery voltage (3.8 V).

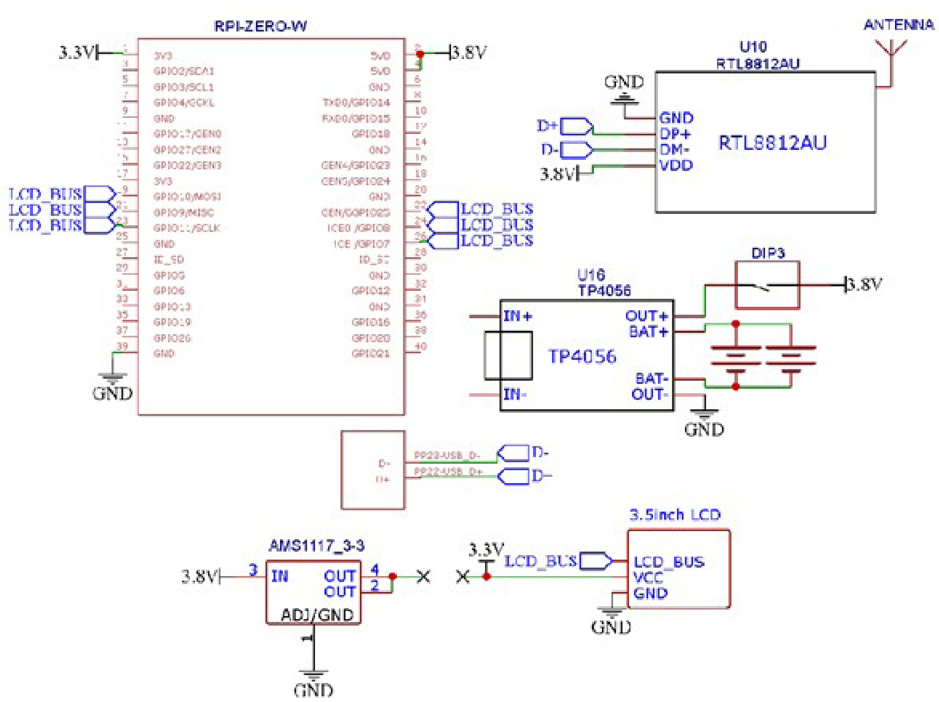

Figure 6. Station schematic (Source: Authors)

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Power management was based on two lithium cells in parallel controlled by a TP4056 module (Figure 6). A critical technical decision was making use of the integrated low-dropout regulator (LDO) integrated into the Raspberry Pi Zero W, which allows stable operation with an input voltage of just 3.5 V. This feature extended battery usage throughout nearly the entire discharge cycle without the need for additional voltage boosting stages, outperforming conventional linear regulators.

Logical Architecture and Software Development

Software development was structured into two blocks: low-level firmware for the vehicle microcontrollers and a high-level application for the control station. All vehicle firmware was developed in C++ using the official ESP-IDF framework, chosen for its granular hardware control and efficient memory management.

Vehicle Firmware (Main and Aux Units)

The Main unit's operation was based on task management, as detailed in its flowchart (Figure 7). After configuring the Wi-Fi network, two independent sockets were established: one for video and another for telemetry and control, preventing image traffic from saturating the command channel. The system captured JPEG frames directly from the sensor to optimize CPU cycles. Before transmission, the frame was fragmented and Forward Error Correction (FEC) was applied, limiting the rate to 10 FPS to ensure link stability. Additionally, this unit acted as an I^2C bridge, relaying commands to the auxiliary unit and managing telemetry autonomously.

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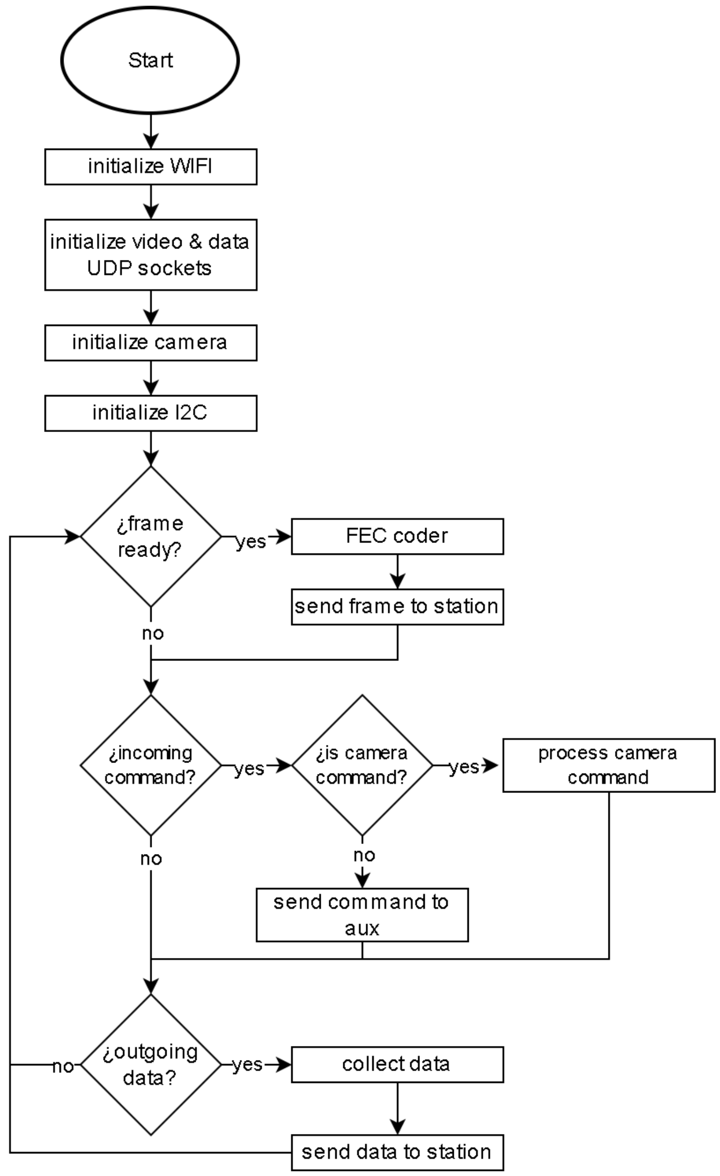

Figure 7. Main unit flowchart (Source: Authors)

The Aux unit was configured as an I²C slave (Figure 8). Its software logic prioritized response speed through an intermediate buffering strategy for the sensors. This method allowed for an immediate response when an I²C transaction was requested by the master unit, delivering pre-prepared data without blocking the processor or affecting overall system timing.

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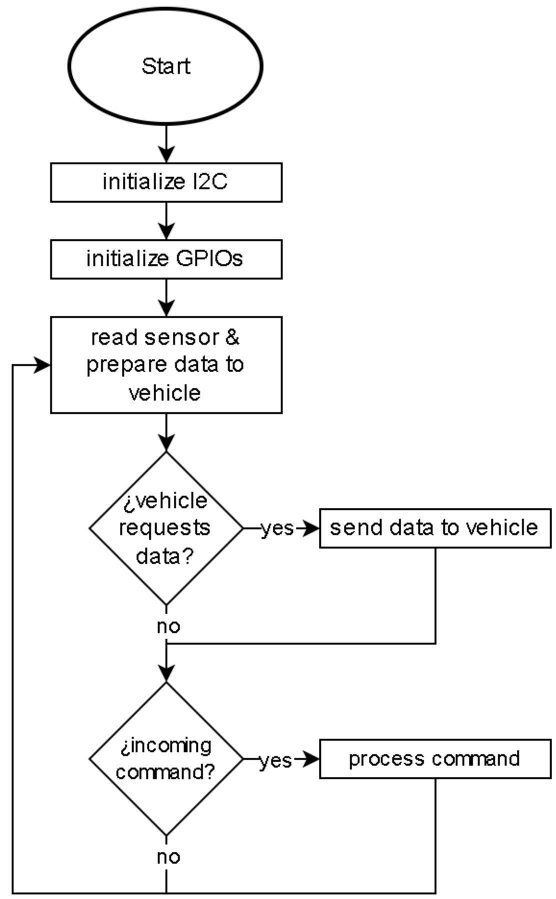

Figure 8. Auxiliary unit flowchart (Source: Authors)

Control Station Application

The station operated on Raspberry Pi OS Lite, configured to launch the control application automatically upon startup. The logical sequence (Figure 9) started with Bluetooth controller synchronization and the creation of the Wi-Fi access point. The graphical user interface was based on the SDL, OpenGL, and ImGui libraries for event and interface management.

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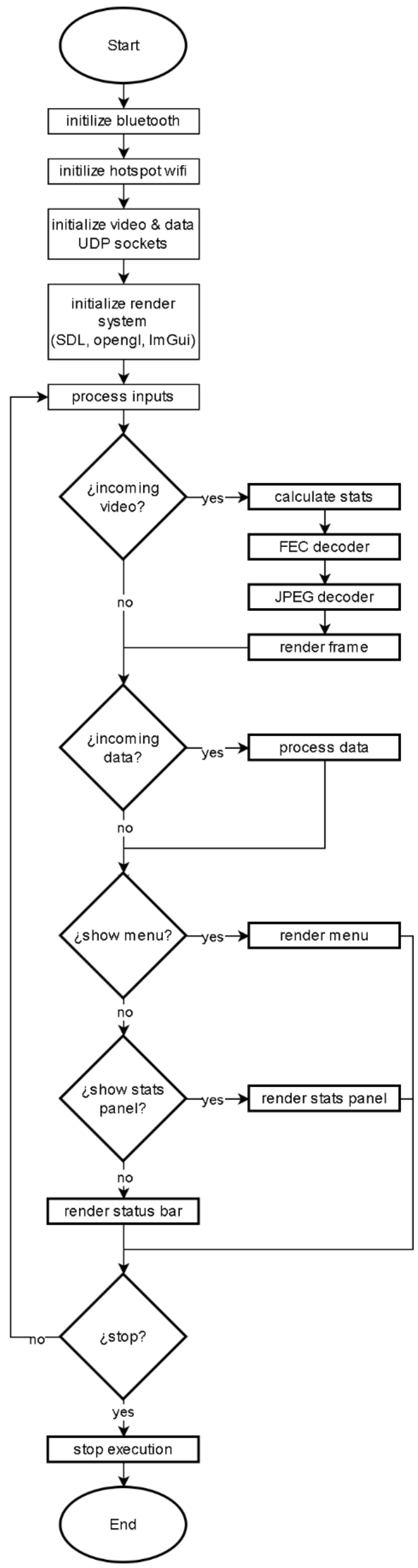

Figure 9. Station flowchart (Source: Authors)

Video handling at the station was a critical task that integrated the FEC reconstruction algorithm to recover information lost due to packet drops. After reconstruction, frames were decoded using the libjpeg-turbo library and rendered via hardware acceleration (GPU). A graphical user interface

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(Figure 10) was overlaid on this signal, displaying a status bar with FPS, signal quality (RSSI), and real-time sensor readings. Finally, a controlled shutdown routine was implemented to ensure the integrity of the operating system file system.

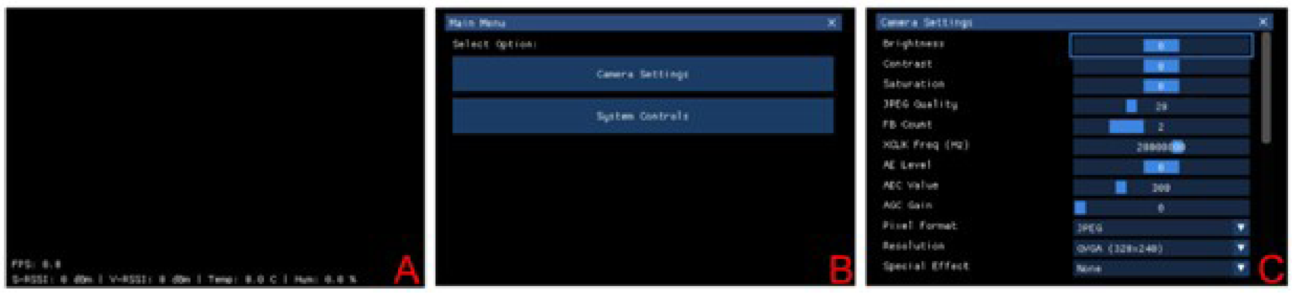

Figure 10. A) Main screen and status bar B) Main menu C) Camera settings menu (Source: Authors)

Experimental Design

To verify the prototype's performance and preliminary operational limits, tests were conducted to evaluate the quality of the telecommunication and visual acquisition subsystems. First, the data link was characterized through path loss tests. The measured variable was the Received Signal Strength Indicator (RSSI), in dBm, recorded directly from the RTL8812AU Wi-Fi adapter driver in the control station. Distance was increased in fixed 5-meter intervals in a direct line of sight under mild weather conditions. Two independent measurements were taken at each of the 35 distance points (n=2). The average and associated uncertainty for each point, defined as the semi-difference between measurements (|x1-x2|/2), were calculated; results are reported in Table 8.

Second, the vision system's response in low-light conditions was evaluated using the integrated lighting modes. Finally, to verify the prototype's general stability during movement, basic locomotion tests were performed in controlled scenarios using various obstacles; these tests focused on corroborating the functional integration of the motor control firmware and do not aim to emulate the extreme friction or irregularity of a real collapse scenario.

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Table 8. Signal strength data (RSSI), average and uncertainty according to distance. (Source: Authors)

Distance (m)	Test 1 (dBm)	Test 2 (dBm)	Average (dBm)	Uncertainty (dBm)
0	-19	-13	-16	±3
5	-31	-29	-30	±1
10	-34	-32	-33	±1
15	-48	-38	-43	±5
20	-50	-47	-48.5	±1.5
25	-50	-48	-49	±1
30	-55	-53	-54	±1
35	-55	-51	-53	±2
40	-57	-52	-54.5	±2.5
45	-60	-56	-58	±2
50	-62	-60	-61	±1
55	-56	-52	-54	±2
60	-55	-51	-53	±2
65	-57	-52	-54.5	±2.5
70	-62	-57	-59.5	±2.5
75	-60	-55	-57.5	±2.5
80	-58	-58	-58	±0
85	-59	-54	-56.5	±2.5
90	-70	-60	-65	±5
95	-60	-58	-59	±1
100	-67	-58	-62.5	±4.5
105	-60	-55	-57.5	±2.5
110	-61	-59	-60	±1
115	-65	-68	-66.5	±1.5
120	-69	-65	-67	±2
125	-72	-69	-70.5	±1.5
130	-71	-60	-65.5	±5.5
135	-66	-62	-64	±2
140	-64	-61	-62.5	±1.5
145	-72	-69	-70.5	±1.5
150	-65	-65	-65	±0
155	-63	-60	-61.5	±1.5
160	-65	-62	-63.5	±1.5
165	-62	-60	-61	±1
170	-69	-66	-67.5	±1.5

Results and Discussion

Data Link Performance and Telemetry

Operational validation of the system was divided into two phases: static stability evaluation and

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open field signal range analysis. In the first stage, with the vehicle stationery at a fixed distance of 5 meters, internal software performance metrics were verified using the custom statistics panel.

As shown in Figure 11, the system recorded an average processing latency of 0.5 ms. This value reflects the time required for the control station to decode and render each frame, confirming that the Raspberry Pi Zero W possesses sufficient power to prevent perceptible delays caused by computational load. Simultaneously, analysis of the data flow revealed a bitrate of approximately 400 kbps. This moderate bandwidth consumption, combined with a sustained reception rate of 10 FPS, validates that the chosen compression and transmission strategy is effective, achieving smooth video without saturating the wireless channel.

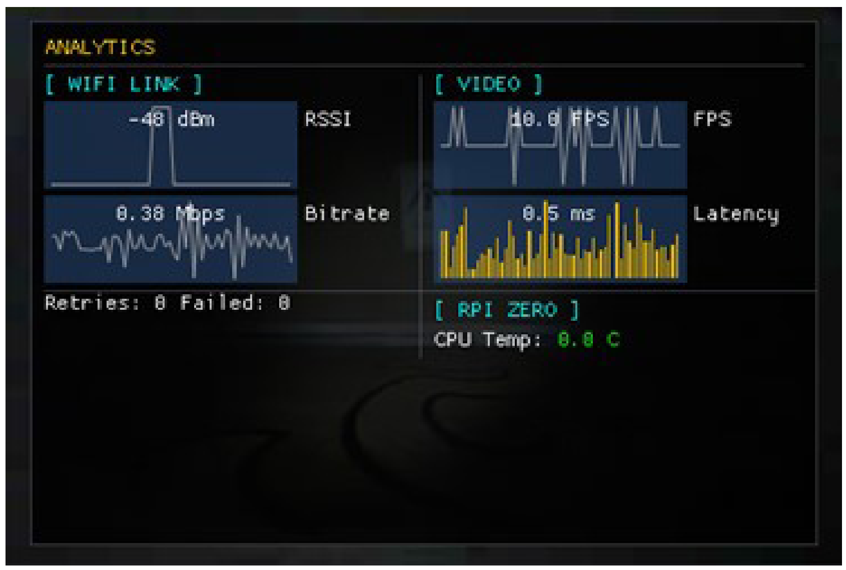

Figure 11. Statistics panel (Source: Authors)

In the second stage, signal degradation was evaluated in relation to distance by recording the RSSI at 5-meter intervals using two independent repetitions per point (n=2; Table 8). Data analysis (Figure 12) suggests link behavior within operating ranges suitable for this preliminary design, starting from an average RSSI of −16.0 ± 3.0 dBm at the origin point. After initial attenuation due to free space propagation, average levels fluctuated mostly between −53 and −62 dBm, with typical uncertainties of ± 1 to ± 2.5 dBm, up to 85 meters. At 90 meters, the average RSSI was −65.0 ± 5.0 dBm, the point at which the video stream showed the first interruptions due to packet loss. As the distance approached 110 meters (−60.0 ± 1.0 dBm), intermittent command reception failures occurred. Transmission persisted discontinuously until total interruption at 170 meters (−67.5 ± 1.5 dBm), identifying this distance as the estimated operational limit under the evaluated line of sight conditions.

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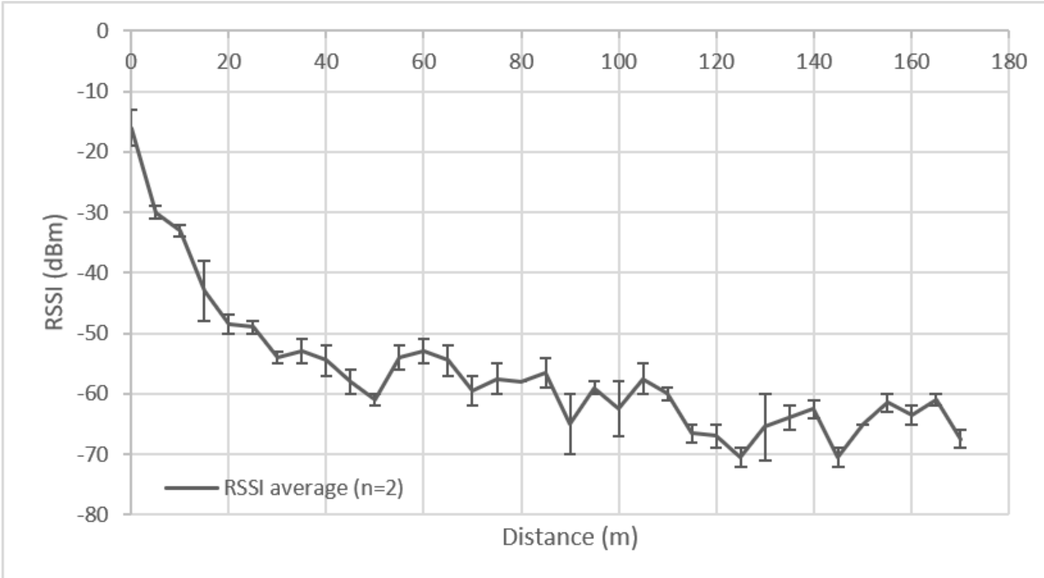

Figure 12. RSSI vs Distance (Source: Authors)

Vision System Evaluation and Energy Consumption

The video subsystem performance was evaluated by setting an operating resolution of QVGA (320x240 pixels). This design choice addresses a critical constraint: higher resolutions exponentially increase processing load on the ESP32 and data volume, saturating the output buffer and destabilizing the Wi-Fi network. Therefore, low latency was prioritized over high definition, a vital factor for real-time teleoperation.

Under this configuration, a comparative analysis was conducted between the two onboard lighting systems: visible light (LED flash) and infrared (IR). The results, summarized in the radar diagram in Figure 13, evaluate performance regarding sharpness, color fidelity, visual range, and energy efficiency. Regarding sharpness, both systems obtained a moderate and identical score, demonstrating that edge definition is limited by resolution and JPEG compression rather than the light source. Conversely, the Flash mode reached the maximum score for color, while the IR mode obtained the minimum rating due to producing monochromatic images.

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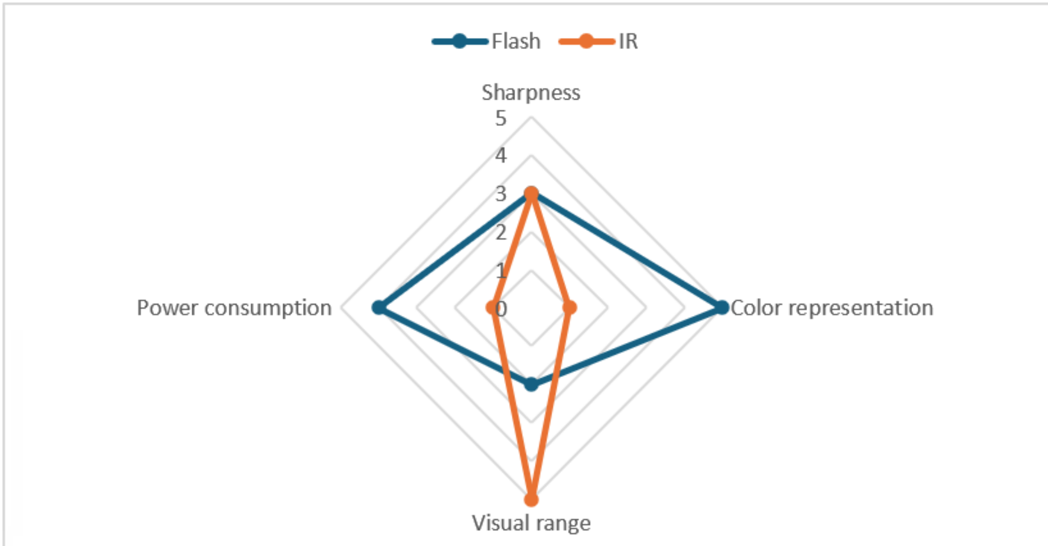

Figure 13. Flash vs IR (Source: Authors)

Tests revealed an inverse technical tradeoff between range and consumption. The IR system demonstrated superior visual penetration but penalized efficiency by demanding 300 mA at 3.3 V. In contrast, the Flash (two 7 V SMT LEDs) consumed only 150 mA, offering limited range but higher energy efficiency for vehicle autonomy. Validation of these data is observed in the captures in Figure 14-A, B y C. In the absence of light (A), operability is nonexistent; with Flash (B), color information is recovered at close range; and with IR (C), its high power is confirmed, although at short distances it causes overexposure that obscures details. This suggests that the Flash is ideal for close inspection, reserving the IR mode for navigation in deep spaces.

Figure 14. A) No lighting B) Flash lighting C) IR lighting (Source: Authors)

Traction Capacity and Obstacle Clearance

The operational limits of the traction system were evaluated on three different scenarios through series of 10 attempts, consolidating success and failure rates in Figure 15.

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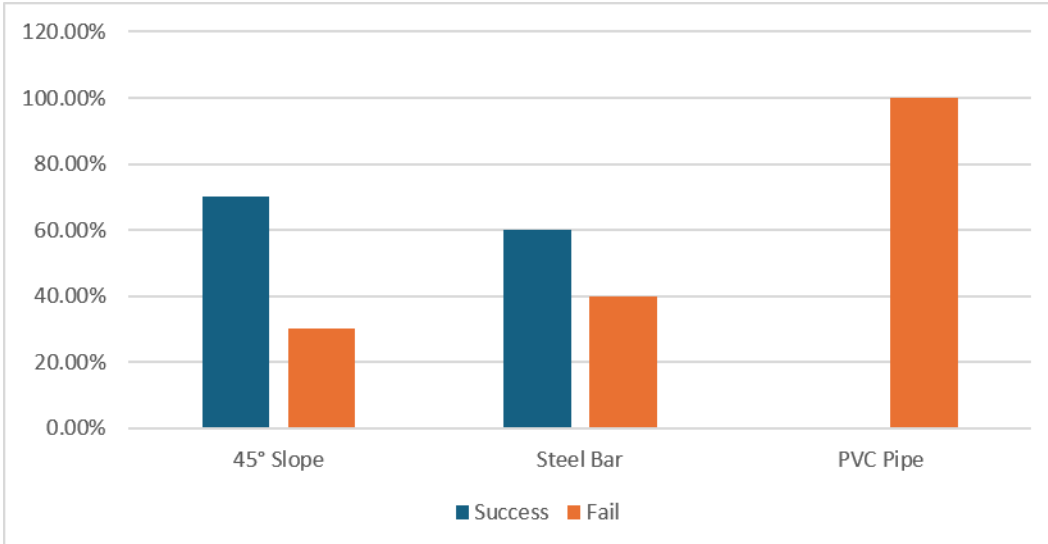

Figure 15. Success rate in locomotion tests (Source: Authors)

The first scenario analyzed performance on a 30-degree incline, obtaining a 70% success rate. During testing, it was evident that the vehicle climbed with difficulty due to constant slippage. Discussion of these failures indicates they were not caused by a lack of motor torque, but rather by the insufficient friction of the smooth 3D printed PLA tracks, which prevented effective power transfer to the ground.

Subsequently, overcoming cylindrical profiles was evaluated (Figure 16). When facing a 15 mm steel bar, the system recorded a 60% success rate. Analysis revealed that the vehicle required momentum to clear the obstacle; at low speeds, the rigid plastic slipped on the steel. Conversely, the 26 mm PVC pipe challenge proved insurmountable (100% failure). This result exposed a critical limitation in the mechanical design: although the vehicle ground clearance (7 cm) is higher than the obstacle, its total length (15.5 cm) is insufficient. The front track managed to scale the pipe, but the low friction of the PVC combined with the short track pitch caused the vehicle to lose rear traction before shifting its center of gravity, leaving it suspended. Overall, the tests showed that the main system limitation lies in the lack of friction of the rigid plastic tracks, a factor that should be addressed by incorporating coatings or rubber elements to improve grip.

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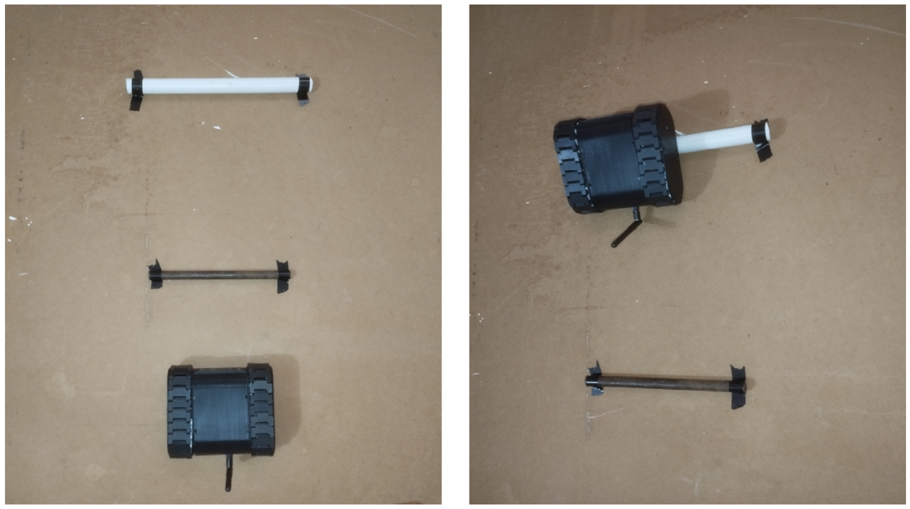

Figure 16. Obstacle test (Source: Authors)

To synthesize the general behavior observed during the experimental evaluation phase, Table 9 summarizes the results of the main estimated and measured operational variables.

Table 9. Summary of system performance metrics (Source: Authors)

Metric	Obtained Result	Condition / Variability
Range	~90 m with continuous stream; 170 m operating limit	Average RSSI −65.0 ± 5.0 dBm at 90 m; −67.5 ± 1.5 dBm at 170 m
Latency	0.5 ms average decoding/rendering per frame	Measured at the station, at a fixed distance of 5 m
Slope	30° incline overcome with 70% success rate	Limited by PLA track friction
Autonomy	Vehicle: 3.47 h theoretical (max measured consumption 1.3 A); Station: 8.8 h theoretical (measured consumption 440 mA)	Estimated from direct current measurements

Conclusions

The development and preliminary evaluation of this low-cost wireless vision and communication system prototype suggests the technical feasibility of the proposed architecture for providing a data transmission channel in exploration applications. The distributed hardware architecture performed functionally under test environment conditions, recording a continuous telemetry and video flow up to an estimated distance of 90 meters; these initial observations point to the potential utility of this electronic system as a sensory extension alternative for the preliminary exploration of restricted access zones.

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Furthermore, characterization of the visual acquisition subsystem indicates that QVGA resolution represents a viable design option for microcontrollers with limited computing capacity, balancing processing demand and the transmission rate required for teleoperation. Additionally, the performance of the hybrid lighting scheme suggests functional complementarity between both modes, providing chromatic information at short distances via LED flash and visualization capacity in low or zero light environments through the infrared channel, which defines base parameters for future characterization phases in more complex scenarios.

Regarding physical displacement, tests in controlled environments allowed for characterizing the basic behavior of the platform. Although the chassis based on open-source models showed stability for carrying the electronics on moderate slopes, it also demonstrated traction limitations and geometric restrictions inherent to rigid materials and the original design dimensions. These observations indicate that while mechanical locomotion fulfills its proof-of-concept role for the electronic system, integration into real deployment vehicles will require more advanced motor platforms adapted to harsh terrain conditions.

Finally, this work proposes a practical alternative for the design of low-cost video transmission and telemetry systems using easily accessible commercial components. The modular nature of the presented electronic architecture allows for considering the possibility of incorporating, in later stages of development, additional sensors for physical variables or gas detection. In this way, the prototype is presented as an initial approach toward exploring low-cost technological tools that can complement the tasks of search and rescue teams.

CrediT authorship contribution statement

Conceptualization - Ideas: Samuel Mora Marín. Data curation: Samuel Mora Marín. Formal analysis: Samuel Mora Marín. Investigation: Samuel Mora Marín. Methodology: Yadira Aracely Fuentes-Rubio. Project Management: Luis Miguel Capacho Valbuena. Resources: Luis Miguel Capacho Valbuena. Supervision: Luis Miguel Capacho Valbuena. Validation: Samuel Mora Marín. Writing - original draft - Preparation: Luis Miguel Capacho Valbuena, Samuel Mora Marín. Writing - revision and editing -Preparation: Luis Miguel Capacho Valbuena, Samuel Mora Marín.

Financing: does not declare.

Conflict of interest: does not declare. Ethical aspect: does not declare.

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