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Prototype of an Intelligent Firefighter Helmet with Improved Localization System and Toxic Gas Detection for Wildfire Scenarios

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***Abstract*—Abstract—This paper describes the redesign of an intelligent firefighter helmet prototype aimed at enhancing safety during wildfire suppression in Honduras. Building upon a base system that monitors vital signs (heart rate and blood oxygen), ambient temperature, posture, and location via LoRa technology, the enhanced design integrates several key improvements: a high-speed calibration GPS module, carbon monoxide (CO) detection, and ruggedized thermal and waterproof housing for the electronic components. Furthermore, a redesigned monitoring interface presents both quantitative and qualitative data to provide comprehensive situational awareness for the user and command center. Experimental results demonstrate a GPS accuracy of ±2.5 m, reliable hazardous gas detection, and structural integrity at temperatures up to 85°C. This system improves occupational safety and emergency management by providing real-time data for informed strategic decision-making in wildfire scenarios.**

***Index Terms*—Smart Firefighter Helmet, Localization Systems, Gas Detection, Wildfire, LoRa, Heat Resistance, Waterproofing**

I. Introduction

Forest fires in Honduras represent a critical threat to both ecological stability and human safety. Recent statistics underscore the severity of this issue, with 3,060 fires recorded in 2023—affecting over 223,501 hectares—and 2,541 incidents documented in 2024 [1]. Firefighters operating in these environments face extreme hazards, including intense thermal radiation, rugged terrain, and exposure to toxic gases. These risks are often compounded by the lack of real-time health and location monitoring systems, which are vital for ensuring personnel safety in high-stress scenarios.

This research builds upon and enhances a previous smart helmet prototype [2]. While the original iteration integrated heart rate, blood oxygen saturation, tilt, and ambient temperature sensors using Long-Range (LoRa) communication and GPS technology, it suffered from technical limitations such as slow GPS calibration and insufficient resistance to heat and moisture. The current work addresses these flaws by implementing a high-performance localization system and ruggedized housing. Furthermore, the updated design incorporates a toxic gas sensor and a refined operational interface tailored to streamline data-driven decision-making at command centers.

The primary objective of this study is to enhance the occupational safety of firefighters and optimize emergency response through the delivery of accurate, real-time data. This paper details the design and fabrication process, evaluates the system's performance and limitations, and discusses future research directions to adapt this technology to the specific needs of local emergency services.

II. Objectives

A. General Objective

The primary objective of this research is to redesign an intelligent firefighter helmet by integrating high-performance localization systems, toxic gas detection capabilities, and enhanced thermal and waterproof protection to improve operational safety in extreme environments.

B. Specific Objectives

- Identify and integrate optimal long-range, low-cost localization technologies suitable for constrained environments.
- Select and validate a toxic gas detection sensor optimized for integration within a wearable firefighting device.
- Enhance the operational interface to provide contextualized data presentation and improve situational awareness for command centers.
- Develop a ruggedized helmet prototype capable of withstanding the extreme thermal and moisture conditions typical of wildfire suppression.

III. State of the Art

An extensive literature review was conducted to examine previous developments in helmet-based technologies designed to aid firefighters. The study specifically focused on advances in location tracking systems, toxic gas detection and measurement, heat-resistant and waterproof materials, and user interface design for real-time monitoring, all of which aim to improve operational safety and effectiveness. The insights gathered from this analysis guided the design of the proposed smart helmet, which incorporates features to monitor vital signs and ensure real-time location tracking during wildfire response missions.

A. Prototype of an Intelligent Firefighter Helmet for Health Monitoring and Location

"Fig. 1" illustrates a smart firefighter helmet prototype developed to monitor vital signs and track users in real time during wildfires [2]. Biometric and environmental sensors were integrated into a heat- and moisture-resistant structure. The core components include an XIAO nRF52840 microcontroller, a MAX30100 heart rate and oxygen saturation sensor, a NEO-7M GPS module, and an Ebyte E32-433T30D LoRa communication module. Custom 3D-printed parts, such as an electronic housing box and an ear pulse oximeter clip, were fabricated using PLA filament. The system acquires data, transmits it via LoRa, and displays it through an interface developed in Visual Studio (see "Fig. 2"). The helmet provides real-time information on heart rate, blood oxygen saturation (SpO_2), ambient temperature, posture, and location, enabling timely responses in extreme conditions.

B. Accident Detection and Location System using LoRa Technology

Another relevant prototype leverages LoRa technology for wireless data transmission, integrating sensors such as the DS18B20 for temperature measurement, the MPU6050 (accelerometer and gyroscope) for fall and posture detection, and the BMP180 barometer for altitude measurement [3]. These components are interfaced with a Raspberry Pi Pico microcontroller, which processes and transmits data through a LoRa SX1278 module. The system includes a lithium 18650 battery with a TP4056 charging module for autonomy, alongside a buzzer and LEDs for local alerts. "Fig. 3" presents the device design. The monitoring interface, implemented on a Raspberry Pi 4B using Node-RED, allows for real-time visualization of movement and environmental conditions ("Fig. 4"). Additionally, the interface features an alarm system for falls, high-temperature exposure, or panic button activation, as well as an emergency register. The ergonomic design, manufactured via 3D printing, ensures seamless integration into the firefighter's Personal Protective Equipment (PPE).

C. Multi-sensor Data Fusion in a Real-Time Support System

This work presents a support system for on-duty firefighters designed to detect falls, physical performance degradation, and elevated levels of carbon monoxide (CO) [4]. The prototype integrates a microcontroller with five key sensors: a 3-axis accelerometer, gyroscope, and magnetometer (all within the ADXL345), a BMP180 barometer, and an MQ-7 gas sensor. Its architecture leverages data fusion techniques to analyze critical events in real time. Information is processed using detection algorithms capable of identifying falls, prolonged inactivity, and hazardous gas exposure. A simple Kalman filter enhances accuracy by stabilizing barometric and gas sensor data. In critical situations, alerts are transmitted to the incident commander via an nRF24L01 wireless module. The system was validated with active firefighters, achieving a detection accuracy of up to 97.96% for key operational events.

Fig. 1. Intelligent firefighter helmet assembled

Fig. 2. Interface designed for monitoring vital signs and tracking the user in real time.

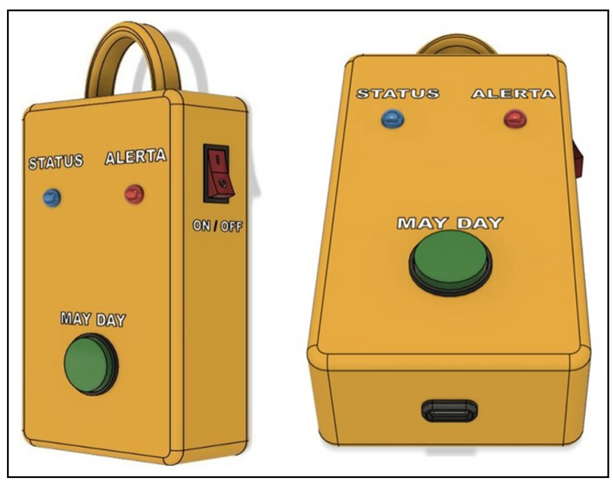

Fig. 3. 3D view of the proposed device

IV. Methodology

A. Approach

This research employs a mixed-methods experimental methodology, combining quantitative and qualitative approaches to develop an enhanced firefighter helmet. This strategy enables the collection of both numerical metrics—such as heart rate, blood oxygen levels, and toxic gas concentrations—and descriptive assessments of the user's physiological

Fig. 4. Interface proposed for the accident detection system

status and environmental conditions. This hybrid approach facilitates multidimensional data acquisition, optimizing the accuracy of real-time monitoring and personnel geolocation during emergency responses.

B. Research Variables

1) Independent Variables:

- **Geolocation System:** Encompasses the positioning technologies implemented, including GPS, GNSS, and potential integration of Ultra-Wideband (UWB).
- **Gas Detection Technology:** Refers to the sensing mechanisms used, such as electrochemical, non-dispersive infrared (NDIR), photoionization, and metal-oxide-semiconductor (MOS) sensors.
- **User Interface Design:** The methodology for presenting processed data to provide a comprehensive quantitative and qualitative description of vital signs, environmental context, and real-time location.
- **Structural Materials:** The materials used for the housing and integration of electronic components into the helmet structure.

2) Dependent Variables:

- **Thermal Resistance:** The capacity of the helmet structure to limit heat flux transfer to the internal electronics.
- **Water Resistance:** The protective capability against liquid penetration and moisture absorption.
- **Power Supply Stability:** The ability to provide regulated voltage and current according to the operational specifications of all integrated components.
- **Ergonomic Design:** The geometric configuration of the housing to ensure seamless integration with the base helmet while maintaining optimal antenna performance.
- **Component Dimensions:** The physical footprint of the modules, balancing size with functional requirements.

C. Applied Techniques and Instruments

The following tools were utilized for the design and development phases:

- **SolidWorks:** Employed for 3D mechanical design and thermal simulation studies.
- **PrusaSlicer:** Used to optimize 3D printing parameters for high-quality additive manufacturing.
- **Arduino IDE:** Used for firmware development and sensor calibration.
- **Visual Studio:** Utilized for designing and programming the monitoring interface for data visualization.

D. Materials

The prototype integration involved the following hardware components:

- Microcontrollers: ESP32 DevKit V1 and Arduino UNO R3.
- Communication: LoRa Ebyte E32-433T30D module.
- Localization: NEO-M8N GPS module with a 1575 MHz 28 dB antenna.
- Sensors: MAX30100 (Heart rate/SpO_2), MPU6050 (Inertial Measurement Unit), DS18B20 (Temperature), and MQ-7 (Carbon Monoxide).
- Fabrication: Custom 3D-printed ABS parts.

E. Study Methodology

The development process followed a structured iterative approach. Initially, a technical literature review was conducted to identify innovative solutions for localization in harsh environments, toxic gas detection, and advanced protective materials.

Unit testing in the Arduino IDE validated each subsystem, ensuring reliable acquisition of physiological, environmental, and location data, as well as robust LoRa communication. Subsequently, the monitoring interface was developed to process and present incoming data from the receiver module in a clear, concise, and organized manner to enhance situational awareness.

Mechanical design was performed in SolidWorks, where thermal simulations were executed to ensure circuit safety under extreme conditions (up to 85°C). Following validation, the housings were fabricated using 3D printing. Finally, the transmission and reception circuits were assembled and subjected to comprehensive field tests to verify the successful integration of the hardware and the operating interface.

V. Results and Analysis

A. Electronic Circuit Redesign

The transition to the ESP32 DevKit V1 (as discussed in Section III) expanded the I/O capabilities but necessitated the integration of external modules for functions previously handled natively. Key components include the MPU6050 for posture tracking [5], the DS18B20 for high-temperature environmental monitoring (up to 125°C) [6], and the NEO-M8N for multi-GNSS real-time location [7].

A critical addition is the MQ-7 sensor for carbon monoxide (CO) detection. CO is a particularly hazardous byproduct of combustion due to its colorless, odorless, and tasteless nature—often termed the "silent killer." Exposure risks range from headaches at 35–400 ppm to fatality at concentrations exceeding 3,200 ppm [4]. While the US OSHA standard sets the maximum safe workplace level at 35 ppm [12], this system is configured to trigger an early alert at 30 ppm, providing firefighters with a crucial margin to deploy respiratory protection.

To ensure signal integrity, pull-up resistors were integrated into the I^2C and one-wire buses to prevent floating states and noise interference. "Fig. 5", "Fig. 6", and "Fig. 7" illustrate the transmitter circuit diagrams. For the receiver, the Arduino UNO R3 and LoRa module were retained, incorporating pull-up resistors and a voltage divider to level-shift the communication logic between the 5V Arduino and the 3.3V LoRa module (see “Fig. 8”).

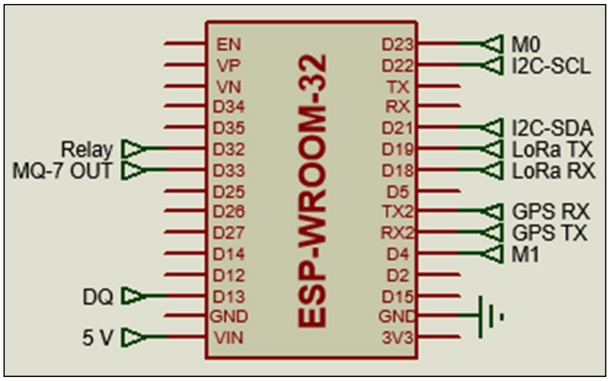

Fig. 5. Transmitter circuit microcontroller wiring diagram

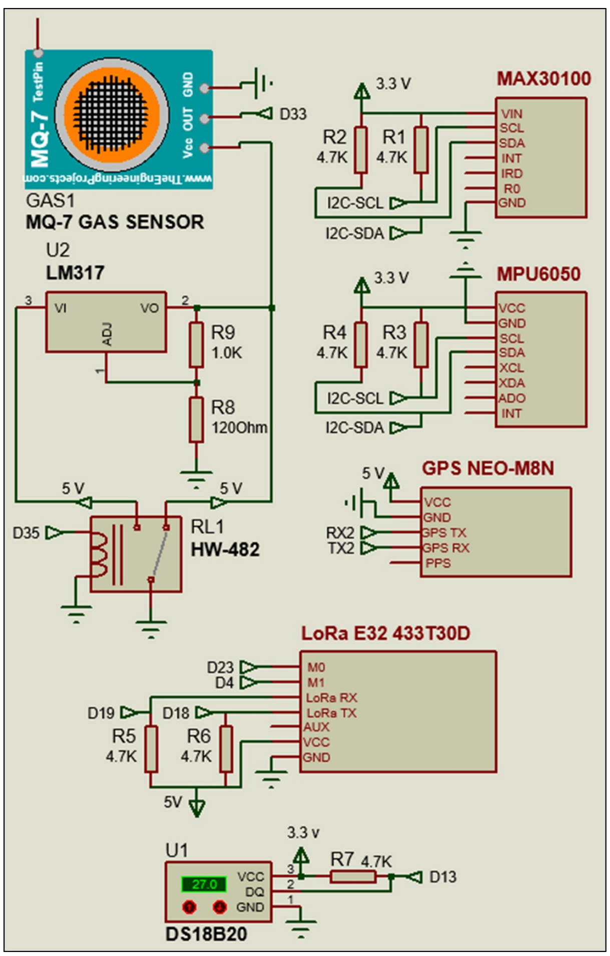

Fig. 6. Transmitter circuit component wiring diagram

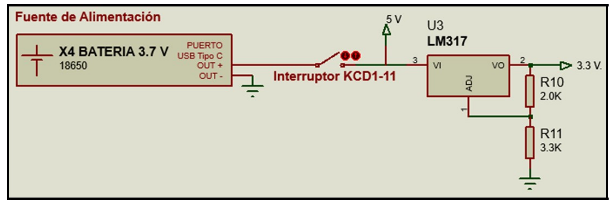

Fig. 7. Transmitter circuit power supply wiring diagram

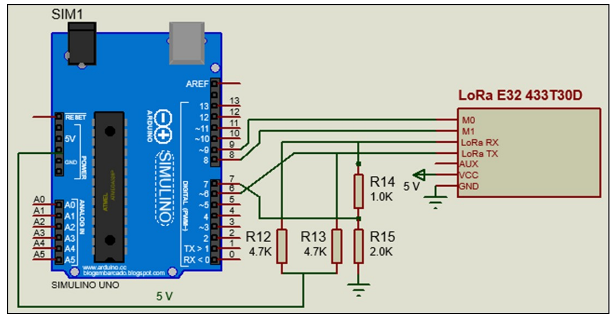

Fig. 8. Receiver circuit diagram

B. Prototype and Mechanical Design

Custom housings were designed in SolidWorks to ruggedize the system. The transmitter case (“Fig. 9”) strategically positions antennas and environmental sensors to avoid interference. A specialized ear-clip for the pulse oximeter was developed to ensure a stable and comfortable fit on the earlobe, facilitating continuous SpO_2 and heart rate monitoring (see “Fig. 10”).

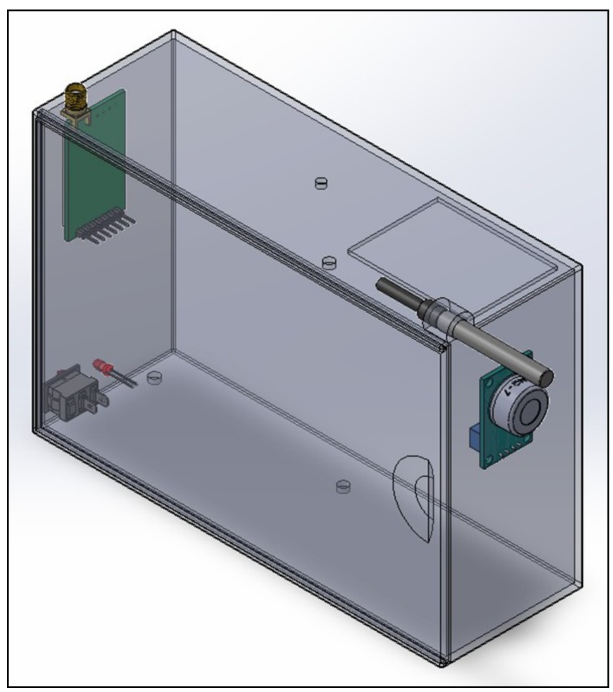

Fig. 9. Isometric view of the transmitter circuit housing

The material selection prioritized thermal stability and moisture protection. Acrylonitrile Butadiene Styrene (ABS) was

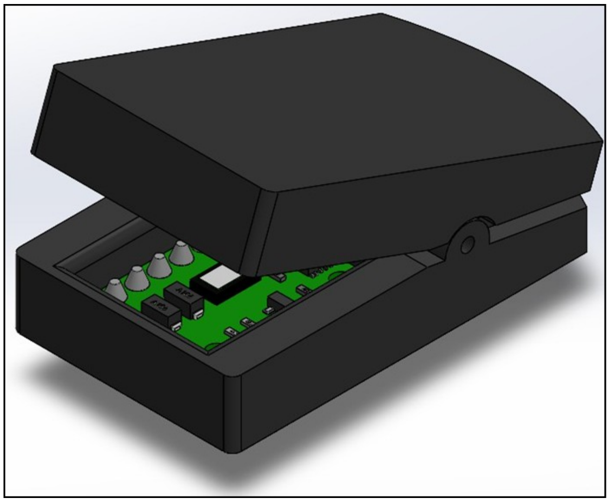

Fig. 10. Isometric view of the ear pulse oximeter designed in SolidWorks

selected for the transmitter housing due to its high impact resistance and superior thermal properties, featuring a glass transition temperature (T_g) of approximately 105°C and a heat deflection temperature (HDT) between 85°C and 105°C [13]. Furthermore, ABS exhibits low water absorption (0.2% over 24 hours), maintaining structural integrity in humid environments [14]. Critical external wiring was encased in flame-retardant silicone rubber tubing, rated for temperatures from -50°C to 125°C [15].

In contrast, the receiver housing was fabricated using PLA, as it is intended for indoor command center use where extreme conditions are not present. This case features dedicated apertures for USB-B and barrel jack power ports, as shown in "Fig. 11".

C. Final Implementation and Testing

The final prototype assembly involved migrating the circuits to a permanent perfboard to ensure mechanical robustness during operation. Screw terminals were utilized to allow for modular maintenance of sensors. The transmitter is powered by a 5V power bank through a rocker switch, while the receiver is powered directly via USB from the monitoring station.

The final intelligent helmet prototype is shown in "Fig. 12". The operational interface, developed for real-time visualization, is organized into four intuitive modules (see "Fig. 13"):

1) **Vital Signs:** Real-time heart rate and oxygenation (SpO_2).
2) **Posture:** Orientation and fall detection via the IMU.
3) **Environmental Conditions:** Ambient temperature and CO concentration levels.
4) **Localization:** Geographic coordinates (Latitude and Longitude) updated via GNSS.

VI. Conclusions

The intelligent firefighter helmet prototype was successfully redesigned, significantly enhancing its operational capabilities

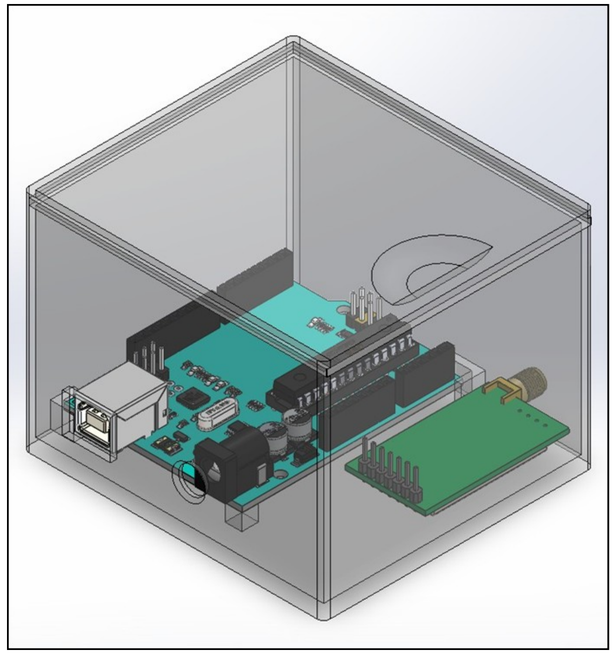

Fig. 11. Isometric view of the receiver circuit housing

in three critical areas. First, the localization system was optimized using a high-performance GPS module and specialized antenna, which achieved rapid satellite signal acquisition and high spatial precision. Second, the integration of a carbon monoxide (CO) detection system provides a vital safety layer, enabling real-time alerts that allow firefighters to take timely protective measures against hazardous gas exposure. Third, the structural integrity and environmental resistance of the device were substantially improved through the implementation of an ABS-based enclosure and flame-retardant insulating tubing, effectively shielding the electronic components from the extreme heat and humidity characteristic of wildfire scenarios.

This research contributes directly to the occupational safety of Honduran firefighters by bridging the gap in real-time monitoring technologies. By providing accurate data on vital signs, environmental hazards, and precise geolocation, the system supports emergency management and facilitates informed, strategic decision-making during high-risk operations. The successful validation of this prototype under controlled thermal conditions demonstrates its potential as a robust tool for improving disaster response in the region.

VII. Recommendations and Future Work

Based on the development and testing of the current prototype, the following directions are proposed for future research and technical enhancement:

- **Advanced Gas Detection:** Future iterations should evaluate electrochemical CO sensors that are less susceptible to high humidity and offer continuous monitoring. While the MQ-7 is cost-effective, its 90-second sensing and 60-second purge cycles, along with its vulnerability to moisture, limit its reliability in active firefighting.

Transitioning to industrial-grade sensors would provide uninterrupted data streams.

- **Environmental Ruggedization:** Although ABS provides excellent thermal resistance, it is prone to degradation under prolonged UV exposure. It is recommended to apply a UV-protective coating or transition to materials like ASA (Acrylonitrile Styrene Acrylate). Additionally, moisture sealing can be improved by integrating custom gaskets for non-standard apertures, potentially manufactured using high-temperature Thermoplastic Polyurethane (HT-TPU) capable of withstanding up to 150°C.
- **Multi-modal Feedback and Communication:** The integration of audible alarms is crucial to alert firefighters of critical physiological or environmental thresholds (SpO_2, temperature, or CO levels) without requiring them to check a display. Furthermore, adding an SOS panic button, real-time voice communication, and low-bandwidth video transmission would significantly enhance situational awareness and coordination with the command center.
- **Scalable Operational Network:** The current point-to-point LoRa architecture can be evolved into a mesh network or a LoRaWAN-based system. This would allow for an interconnected "Firefighter Network" where multiple units can be monitored simultaneously, enabling peers and commanders to share location and health data in real time across the entire fireground.

Fig. 12. Isometric view of the improved intelligent firefighter helmet prototype

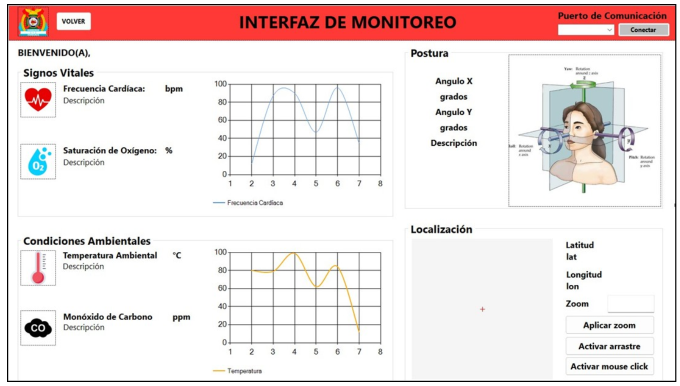

Fig. 13. Design of the operating interface

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