ISBN: 978-628-96613-1-6. ISSN: 2414-6390. Digital Object Identifier: https://dx.doi.org/10.18687/LACCEI2025.1.1.1685

Prototype of an Intelligent Firefighter Helmet for Health Monitoring and Location in Forest Fire Situations

Alan Mauricio Romero Soto
Facultad de Ingeniería
Universidad Tecnológica Centroamericana (UNITEC)
Tegucigalpa, Honduras
amromero@unitec.edu

Rafael Eduardo Flores Reyes
Facultad de Ingeniería
Universidad Tecnológica Centroamericana (UNITEC)
Tegucigalpa, Honduras
floresrafael279@unitec.edu

Fávell Eduardo Núñez Rodríguez
Facultad de Ingeniería
Universidad Tecnológica Centroamericana (UNITEC)
Tegucigalpa, Honduras
favell.nunez@unitec.edu

***Abstract*—This research project focuses on developing a prototype of a smart firefighter helmet integrating advanced technology to enhance safety and efficiency during wildfire operations. The helmet includes a pulse oximeter for health monitoring, a GPS module for precise location tracking, a gyroscope for position detection, and environmental sensors for temperature recording. Extensive research ensured the selection of suitable sensors, prioritizing accuracy and reliability under extreme conditions. The development process involved implementing a wireless communication system based on LoRa technology, enabling rapid and secure data transmission from the helmet to a central platform. This feature enhances operational coordination, facilitating quicker and more precise emergency responses, thereby optimizing firefighter safety and efficiency. The helmet's design emphasizes comfort for prolonged use, incorporating a custom clip for the pulse oximeter to ensure a secure fit without interfering with field operations.**

The smart firefighter helmet represents a significant advancement in safety and emergency management technology. By monitoring firefighter health, providing precise location tracking, and measuring critical environmental conditions, the helmet improves operational coordination and strategic decision-making. In dynamic and hazardous situations like wildfires, this smart helmet is crucial for ensuring firefighters are well-monitored and equipped, enabling a safer and more effective emergency response.

***Index Terms*—GPS module, Gyroscope, Pulse oximeter, Smart firefighter helmet, Wireless communication**

I. Introduction

Firefighter helmets are a crucial piece of personal protective equipment during fire situations. They are designed to withstand high temperatures, protecting the skull and face from intense heat and direct flames. Their robust structure also helps maintain the firefighter's integrity in hazardous environments. Helmets are often equipped with visors or face shields to protect the eyes and face from burns and injuries caused by splashes of flammable liquids. Additionally, some models include integrated communication systems that facilitate coordination among team members in emergency situations.

According to the National Forest Conservation Institute (2024), fires are more likely due to high temperatures and a lack of rain caused by the El Niño phenomenon. In the first three months of 2024 alone, 910 forest fires have been reported, affecting 41,462 hectares. Firefighter teams are responsible for resolving these situations, putting their lives in grave danger. On March 8, 2008, a major fire on Upare Hill claimed the lives of nine people who died from intoxication and burns while fighting the fire. Many other tragic cases like this exist, and due to the high number of fires reported in 2024, the statistics of firefighters affected by fires may increase.

The safety of brigade members and firefighters is of utmost importance when facing a forest fire. These brave workers face extremely dangerous conditions, such as intense heat, dense smoke, rugged terrain, and the possibility of sudden changes in wind direction. This project aims to monitor the health status and location of brigade members in forest fire situations to ensure the safety and well-being of those who risk their lives to protect communities and ecosystems affected by forest fires.

II. Objectives

The general objective is to design and construct a smart firefighter helmet that integrates sensors to monitor the health status of firefighters and track their precise location during wildfire operations. The specific objectives include:

- Researching and selecting the most suitable sensors to measure relevant health parameters under extreme firefighting conditions.
- Implementing a location system to track the precise location of firefighters during wildfire operations.

- Creating a wireless communication system that allows the transmission of data collected by the helmet sensors to a central platform.
- Designing a helmet that integrates the various sensors and communication modules, making it suitable for use by firefighters.

III. State of the Art

A thorough research was conducted to explore existing works related to assisting firefighters through various technologies implemented in their helmets. This research aimed to identify advancements in sensor integration, communication systems, and design enhancements that have been previously developed to improve firefighter safety and efficiency during operations. The findings from this research informed the development of a new smart firefighter helmet, integrating state-of-the-art technologies to monitor health status and track precise location during wildfire operations.

A. Multipatient Monitoring System using Arduino Mega

The proposed system utilizes an Arduino Mega, a MAX30102 sensor, a pulse sensor, an LM35 temperature sensor, and an LCD display. This system continuously monitors patients' vital signs and detects any irregularities. Results are transmitted wirelessly using Zigbee due to its ability to meet guaranteed delay requirements for telehealth monitoring systems. In the event of detecting anomalies, the system notifies medical personnel about the irregular parameter and minimizes the need for manual monitoring by medical professionals. [1]

B. Real-time wildfire detection, monitoring, and warning system using Arduino

This system utilizes temperature and humidity sensors, a smoke sensor, a flame sensor, an Arduino microcontroller, and a GPS module. The fire warning system was developed using a software application called Blynk. Figure 1 depicts the connection diagram used to create the system.

The system incorporates a three-indicator widget and a value display in the application. When the smoke sensor, flame sensor, or temperature sensor sends a signal, Blynk sends a notification indicating the presence of nearby fire. The value display widget showcases the latitude and longitude of the device when it received the fire signal. The map widget determines the exact location of the transmitter box and collects the sensor data, which is then transferred via the GPRS/WiFi network. Finally, the data is converted into digital signals, and an alarm signal is sent upon fire detection. [2]

C. Real-time Soldier Health Monitoring System using IoT

This system utilizes Internet of Things (IoT) technology, specifically the ESP32 microcontroller, due to its efficient wireless transmission capabilities to a centralized monitoring station. The system adheres to privacy norms and rules, prioritizing the protection of soldiers' individual health data.

The system comprises a temperature and humidity sensor, a pulse sensor, a NEO-7M GPS module, the ESP-32 microcontroller, a relay, a power supply, a hot plate, a buzzer, and a Blynk Cloud. [3]

D. Forest fire detection, prediction and behavior analysis system using IoT

This system utilizes a network of wireless sensors to efficiently detect and analyze fire behavior, providing real-time data on fire spread, speed, and direction. It is based on changes in environmental parameters, including temperature, relative humidity, and the Chandler Combustion Index (CBI). The system is divided into the data processing phase, fire detection phase, behavior analysis phase, and prediction phase.

The devices used in this system include a Waspmote, which is a sensor specially designed for developers that works with different protocols such as ZigBee, Bluetooth, and GPRS, an XBee Pro transceiver, a rechargeable lithium-ion battery ICR18659H-1S3P, a temperature sensor (MCP9700 A), and a relative humidity sensor (808H5V6SM). [4]

E. IoT monitoring system to detect and record air quality, fire pollutants, and wildfire smoke for firefighters

This work by Lioliopoulos presents a unique innovation that significantly benefits firefighters worldwide. The system's primary function is to acquire real-time data on pollutant values, continuously transmit this data to headquarters, and store and manipulate the data. This is achieved through a wireless network that incorporates multiple sensor systems communicating with a remote server. The server is responsible for data storage and manipulation, as well as real-time display of pollutant values and air quality.

The system utilizes a Raspberry Pi, a set of Libelium Smart Spot models, a 4G antenna, a SIM7600E Module, a particle sensor, a GPS antenna, a portable external battery, and a web application to achieve its objectives. [5]

F. C-THRU: Scuba Diving Helmet with smoke

The C-Thru Smoke Diving Helmet represents a significant innovation in the technology used by firefighters during fire search and rescue operations. This helmet incorporates several advanced technologies, including head-mounted screen projection, retro-reflective image capture, optical thermal imaging, cloud computing, active noise cancellation, and smart shock-absorbing and heat-resistant materials.

By leveraging these technological advancements, the C-Thru helmet aims to overcome critical challenges faced by firefighters in dense smoke environments, such as limited visibility, communication difficulties, and the need to assess and record fire causes. "Fig. 1" depicts the C-Thru device in action, showcasing its potential to revolutionize firefighting safety and effectiveness.

One of the key features of the C-Thru helmet is its capability to provide an enhanced view of the interior smoke environment through imaging that displays the surrounding geometry, as illustrated in "Fig. 2". Moreover, the helmet

Fig. 1. C-Thru Scope [6])

selectively enhances ambient sounds, enabling firefighters to conduct more accurate and efficient searches for victims trapped in fires. This technology, akin to augmented reality, is currently being adopted by major air forces worldwide, highlighting its relevance and effectiveness in challenging operational environments. [6]

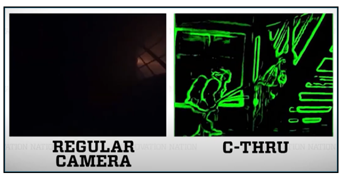

Fig. 2. Comparison of view using a normal camera and the C-Thru helmet [7]

The C-Thru helmet is anticipated to have a profound impact and offer substantial benefits by significantly reducing casualties in fire events through the enhancement of rescue operation efficiency. Moreover, by providing a clearer and more detailed view of the environment, this helmet will assist firefighters in more effectively assessing and documenting the causes of fires, thereby contributing to the prevention of future incidents. The adoption of the C-Thru helmet represents a substantial advancement in the safety and effectiveness of firefighters during fire rescue operations, with the potential to positively impact both the protection of human lives and the preservation of the environment.

G. Firefighter helmet that uses artificial intelligence to see through smoke

This helmet is a great innovative technological breakthrough in the field of firefighting. This device leverages artificial intelligence along with a variety of advanced sensors, thermal cameras, and radar technology to provide firefighters with enhanced vision within densely smoky environments. Artificial intelligence plays an important role in interpreting the data collected within the fire and providing vital real-time information to firefighters. This information only helps firefighters locate and rescue victims more quickly and effectively, even in extremely challenging conditions such as dense smoke. Looking at “Fig. 3”, the sensors and thermal camera are placed on the front of the helmet, while the microcontrollers and devices responsible for sending the information are placed on the back of the case. [8]

Fig. 3. Smart firefighter helmet that uses [9]

The AI-powered helmet interprets data from multiple sensors using deep learning and other advanced algorithms to automatically detect victims’ locations. Deep learning is crucial for the helmet as it enables accurate processing and understanding of the vast amount of data collected by the sensors and the thermal camera. Additionally, the helmet can estimate the positions of firefighters, providing real-time information to aid in rescue efforts. “Fig. 4” depicts the image captured by the thermal camera, detecting the position of people near the firefighter. This technological advancement signifies a significant change in how firefighters approach emergencies. [9]

Fig. 4. Perspective of the firefighter wearing the helmet [8]

H. Technologies used to fight wildfires

In the field of firefighting technologies, voice communication is emerging as a critical element in both routine and emergency operations. To address communication challenges, the use of alternative technologies, such as lower carrier frequencies and repeaters, is proposed to enhance reliability and range while reducing the communicative load by monitoring equipment activities. “Fig. 5” showcases one of the most modern helmets used by firefighters in Australia. These helmets offer connectivity with a wide variety of radios, with the possibility of developing new interfaces as needed by customers. [10]

In forest firefighting, the use of unmanned aerial vehicles (UAVs) has become prominent due to their ability to replace manned aircraft in tasks such as early detection and fire surveillance. Equipped with advanced technology such as infrared cameras and sensors, these UAVs allow constant and efficient surveillance of forest areas, even in difficult terrain. Recent advances include specialized drones designed to investigate signals from ground cameras, solving false signal problems, and maximizing flight time. This technological

Fig. 5. Gallet F1XF communication and hearing protection systems [11]

evolution offers a promising prospect for further improving wildfire monitoring systems using artificial intelligence and surveillance data analytics [12].

The use of live-streaming body cameras (body cams) in firefighting has been recognized as a crucial tool to provide detailed, real-time information to the logistics team. These body cams must meet specific criteria, such as high streaming quality, low latency, streaming capability over different networks, inclusion of GPS information, durability, and adequate battery life. In forest fires, body cams enable real-time resource location, improving coordination and firefighter safety. Although limitations exist in the availability and technology of body cams, further improvements and developments are expected to make them even more effective and beneficial for fire response teams. "Fig. 6" provides an example of a body camera with integrated GPS used by security forces and firefighters [13].

Fig. 6. ZEPCAM BODYCAM T2+ [14]

IV. Methodology

A. Approach

This project will employ a mixed experimental approach. A firefighter helmet will be developed using a combination of quantitative and qualitative techniques to monitor the wearer's vital signs and locate the firefighter during wildfires. The experimental component will include testing and evaluating the prototype helmet in controlled environments to assess its efficiency and performance. This mixed approach aims to provide a comprehensive understanding of the development and impact of the vital signs and localization monitoring helmet in emergency situations such as forest fires.

B. Research Variables

Dependent Variables:

1) Vital Signs Monitoring Sensors
2) Firefighter Location
3) Communication between devices
4) Thermal Resistance

Independent Variables:

1) Helmet structure
2) Power source
3) Helmet design
4) Device operation

C. Applied Techniques and Instruments

1) SolidWorks: Design of the helmet and clamp for the pulse oximeter.
2) PrusaSlicer: 3D Printing for the Earlobe Pulse Oximeter Clamp.
3) Arduino IDE: Programming of sensors and communication modules.
4) Visual Studio 2022: Interface Programming for displaying data obtained from sensors and communication modules.

D. Materials

1) XIAO Nrf52840 Sense Microcontroller
2) Modulo Lora Ebite A32-433T30D
3) NEO 7M GPS Module
4) Heart rate and oxygen sensor MAX30100
5) Arduino UNO
6) Protoboard
7) 3D printed parts
8) Firefighter helmet

E. Study Methodology

To ensure the successful completion of the project, the different procedures were divided into stages.

In the first stage, a comprehensive literature review was conducted to gather data on monitoring vital signs and tracking the location of firefighters during forest fires. Vital signs, particularly heart rate and oxygen saturation, were identified as crucial indicators. To measure these vital signs, a pulse oximeter was selected, with the earlobe identified as the most comfortable location for placement.

The research also considered the method of data transmission, given the remote and often signal-challenged environments where forest fires occur. After careful evaluation, LoRa wireless technology was deemed the most viable option due to its ability to transmit data over long distances, even in areas with no signal.

To validate the research findings, an interview was conducted with the Honduran fire department in Tegucigalpa. The interview highlighted the need for advanced firefighting technologies. Additionally, key insights were gathered for the helmet design, including the inclusion of sensors for environmental data, a sensor for firefighter positioning, and the requirement for the helmet to be both fire and water-resistant.

V. Results and Analysis

The primary aim of this project was to develop a smart firefighter helmet capable of detecting vital signals and determining the wearer's precise position and location during firefighting operations. The integration of various sensors and communication modules aimed to provide real-time data for monitoring the wearer's health and ensuring their safety in dynamic and hazardous environments. This section presents the results of testing the components' integration and functionality, along with the analysis of the helmet's performance in controlled testing environments.

A. Electronic Circuit

To evaluate the integration and functionality of the components, both a transmitter circuit and a receiver circuit were designed and tested. The transmitter circuit included components necessary for collecting biometric and location data: the MAX30100 sensor for heart rate and blood oxygen saturation, the NEO-7M GPS module for real-time location tracking, the XIAO nRF52840 microcontroller for data collection and device orientation/movement recording, and the LoRa module EBYTE E32 for long-distance data transmission. "Fig. 7" depicts the transmitter circuit diagram, and "Fig. 8" shows the receiver circuit diagram.

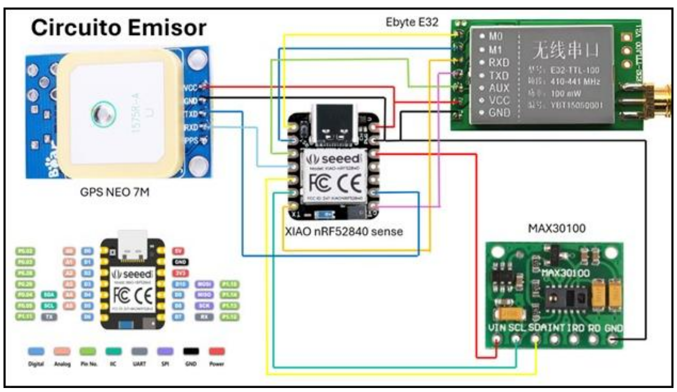

Fig. 7. Transmitter circuit

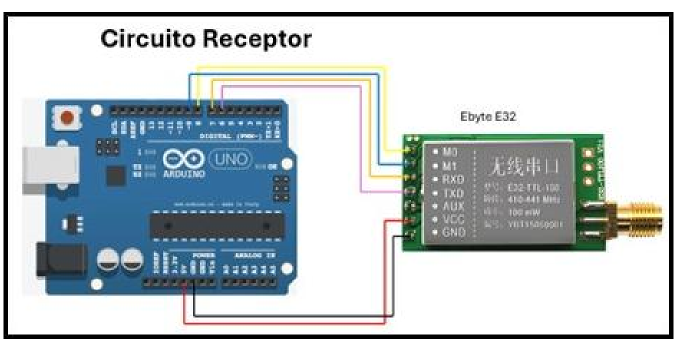

Fig. 8. Receiver circuit

B. Design of Housing for the Max30100 Pulse Oximeter

A specific housing was designed for the Max30100 pulse oximeter to create a clip for placement on the earlobe. This design ensures secure and precise insertion of the sensor into the clip, facilitating accurate heart rate and oxygen saturation measurements. The clip was designed for stable attachment to the earlobe, enabling accurate and continuous readings for the wearer. "Fig. 9" and "Fig. 10" illustrate the complete design of the housing for the Max30100 Pulse Oximeter.

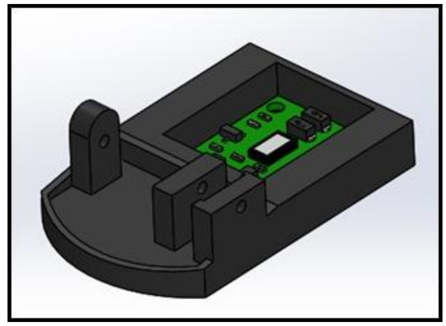

Fig. 9. Isometric View of the Housing with the Max30100 Sensor

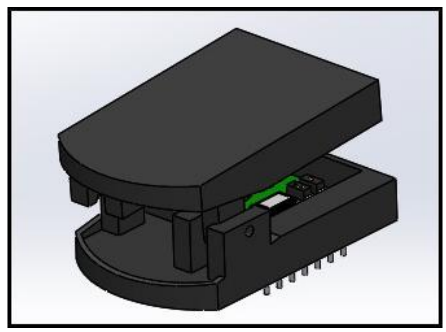

Fig. 10. Isometric View of the Housing

C. Firefighter Helmet Design for Prototype

A design was developed for the firefighter helmet prototype, including a specific clip for the MAX30100 pulse oximeter sensor for continuous monitoring of the user's heart rate and blood oxygen levels. An external battery was added to power the emitter circuit, ensuring a constant and reliable power supply. A switch for manual control of the circuit and a led indicating the power status were also included, enhancing the helmet's functionality and safety. A special box was designed to house the emitter circuit components, protecting them in adverse conditions. The main objective was to ensure that the pulse oximeter clip was comfortably positioned on the ear of the helmet wearer, minimizing the distance between the clip and the emitting circuit for accurate and continuous measurements. "Fig. 11" provides a visual representation of the described design.

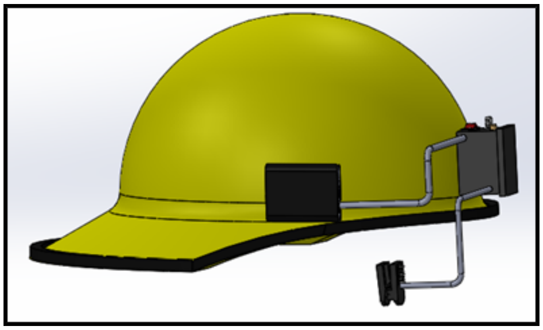

Fig. 11. Firefighter Helmet Design

D. Final Test

Final tests were conducted to verify the functionality of all sensors working together in the firefighter helmet, the wireless communication system, and the user interface. The transmitter circuit was connected to a portable 5-volt battery, and the receiver circuit was connected to a computer, where the interface received all the data sent through the serial port. "Fig. 12" shows the helmet during the final test and how it would look during operation. The interface,"Fig. 13", displayed data collected by the sensors, including heart rate, blood oxygen percentage, environmental temperature, XYZ axes with their magnitude, and a circular graph indicating the firefighter's posture, along with latitude and longitude data displayed on a map.

Fig. 12. Firefighter Helmet Assembled

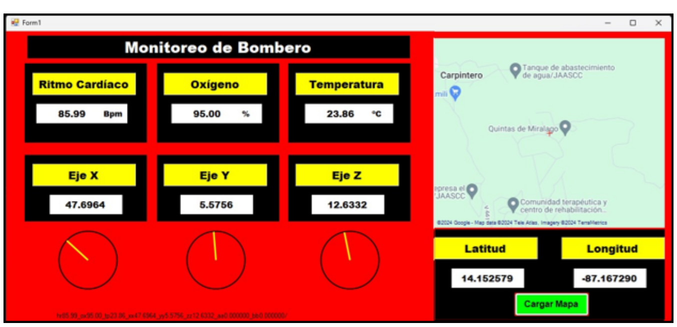

Fig. 13. Final Interface in Operation

VI. Conclusions

The development of a smart firefighter helmet integrating sensors for health monitoring and precise location tracking during wildfire operations represents a significant advancement in firefighter safety and operational efficiency. Through meticulous research, the most suitable sensors were selected to ensure accurate data collection under extreme conditions. The implementation of a location system enabled real-time tracking of firefighters, enhancing operational coordination and safety. The integration of an efficient wireless communication system facilitated the rapid transmission of data to a central platform for analysis. The helmet's design effectively incorporated various sensors and communication modules, ensuring its functionality and usability for firefighters. Overall, this project has the potential to greatly improve firefighting operations by providing critical real-time data for informed decision-making and personnel safety.

VII. Recommendations and Future Work

- **Material Enhancement:** Consider utilizing more robust and heat-resistant materials, such as ABS, for the pulse oximeter casing and component box on the firefighter's helmet. PLA, while suitable for prototyping, may deform at lower temperatures than ABS, potentially compromising component durability.
- **GPS Module Improvement:** Evaluate alternative GPS modules that do not require calibration or that can be calibrated more easily, particularly in enclosed areas. The current NEO-7M GPS module's calibration process could delay operations and pose challenges in certain environments, potentially affecting usability.
- **Waterproofing Electronics:** Given the frequent exposure to water in firefighting operations, it is crucial to waterproof electronic components to ensure functionality and durability in wet conditions.
- **Additional Features:** Consider integrating more features into the firefighter helmet, such as a real-time camera for enhanced monitoring, a voice communication system for improved coordination, and a display screen for presenting vital signs and offering functions like an emergency button or toxic gas detection.

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