

Patient-Worn Bracelet for Real-Time Heart Rate and SpO₂ Monitoring with Predictive Health Analysis in Hospital and Remote Settings

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Abstract: This study presents a wearable health monitoring system designed as a smart structural system that integrates mechanical design, and embedded sensing to continuously track heart rate and SpO₂ levels in real time. The need for such a system arises from the growing demand for accessible healthcare, particularly for individuals with limited access to regular medical check-ups. Hospitals face challenges in providing timely care due to overwhelming workloads when staff are responsible for monitoring many patients. This system addresses that issue by offering a tool that facilitates more efficient patient monitoring through intelligent material-structure integration. The system integrates a MAX30102 sensor with an ESP32-C3 Xiao microcontroller and uses fuzzy logic algorithms to classify health conditions, such as Normal or Hypoxemia, in real time. Data is wirelessly transmitted from the sensor to a mobile application using Bluetooth BLE and is then stored in a Firebase database for easy access by healthcare professionals. The mobile application provides healthcare providers with immediate access to the latest health data, allowing them to take action if needed. Testing demonstrated successful real-time data transmission with classification accuracy of health status categories. The system reduces the physical effort required by healthcare staff to check on patients individually, offering a more efficient method of monitoring. Energy efficiency analysis shows optimized power consumption enabling extended battery life suitable for continuous monitoring. This study represents a practical and sustainable solution for enhancing healthcare delivery by allowing for remote monitoring of patients and improving workflow in medical settings. The system is designed with scalability and sustainability in mind, incorporating recyclable materials and modular components that facilitate future upgrades or sensor additions.

Keywords: Wearable Health Monitoring, Smart Structural Systems, Flexible Materials, Real-Time Tracking, Fuzzy Logic, Bluetooth BLE, SpO₂ Monitoring, ESP32 Microcontroller.

1. INTRODUCTION

Wearable health devices have become increasingly popular for monitoring various health parameters, including heart rate and blood oxygen levels (SpO₂) (Piwek *et al.*, 2016). These devices represent an evolution in smart structural systems, where the integration of flexible materials, embedded sensors, and computational intelligence creates a unified platform for continuous health monitoring. Traditional methods of monitoring, such as periodic check-ups, often miss subtle changes in a patient's health status. In contrast, wearable technology implemented as smart material-structure systems allows immediate data access by health professionals and users at any moment in time, anywhere. The development of such systems requires careful consideration of mechanical design, material selection, structural integrity, and sustainability alongside electronic functionality.

This study presents a wearable bracelet that exemplifies the principles of smart structural systems through the integration of biocompatible flexible

polymers, conductive materials, and embedded sensing technologies. The MAX30102 sensor (Maxim Integrated, 2014) and ESP32-C3 Xiao microcontroller (Seeed Studio, 2023) have been integrated into a mechanically robust bracelet structure designed to withstand repeated bending, fastening cycles, and the rigors of daily use. The structural design prioritizes flexibility to ensure comfortable wear while maintaining the mechanical stability necessary for accurate sensor contact and reliable measurements. The bracelet continuously monitors heart rate and SpO₂ and transmits this information to an Android application for real-time data analysis, alerting users or health professionals in case any abnormality is found.

The traditional care system is effective but quite limiting, especially in cases concerning geographical movement problems for patients (Onyile *et al.*, 2013). It relies on regular check-ups that may not easily facilitate the detection of gradual changes affecting the patient's health status. Current remote monitoring systems rely on basic threshold-based alerts which cannot detect less obvious changes in health data (Fitzgerald, 2024). These are only reactive, not proactive. For example, simple alarms trigger in cases of SpO₂ falling below a certain value. What is needed is a continuous health monitoring system that can analyze real-time data to

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detect problems early. In the absence of such systems, healthcare professionals have to be reactive instead of proactive. Additionally, when hospitals become busy or packed with patients (Kosmo Online, 2023), staff members are often required to physically monitor and collect patient data one by one, leading to significant physical strain. This process becomes especially challenging in larger healthcare settings where staff fatigue increases with the number of patients needing attention.

By implementing continuous, remote health monitoring systems built on smart structural principles, healthcare staff can focus on more critical interventions rather than routine data collection, alleviating stress and improving the overall efficiency of patient care. The objective of this study is to provide a convenient, sustainable, and accessible health monitoring solution that works effectively whether the patient is at home or in the hospital. This system ensures that health professionals can monitor patient data remotely, thus improving the efficiency of care and reducing the burden on staff members, particularly in busy hospital settings. The structural design emphasizes long-term durability and sustainability through the use of recyclable materials and energy-efficient components.

There are a number of wearable health monitoring systems, but they have their limitations from both electronic and structural perspectives. For instance, Internet of Thing (IoT) pulse oximeters using the ESP32 microcontroller and MAX30100 sensor can track heart rate and SpO₂ and send this data to a cloud platform or mobile application for remote monitoring. However, they only trigger alerts when health metrics fall outside predefined limits, which doesn't allow for proactive detection of health issues (Electronic Wings). Furthermore, many existing wearables lack consideration for mechanical durability, material biocompatibility, and structural flexibility necessary for extended wear. Other systems, such as Heart Rate and Blood Oxygen Monitoring Using IoT, focus on monitoring and providing supplemental oxygen but still rely on basic thresholds for alerts (Al-Emran *et al.*, 2020). More advanced systems, like the smart framework for heart rate monitoring, use machine learning to predict abnormal heart rates but don't include SpO₂ monitoring or the fuzzy logic that could enhance the accuracy of health predictions (Padmavathi *et al.*, 2019). Notably, few studies address the wearable device from a comprehensive smart structural systems perspective, integrating materials engineering, mechanical design, and embedded intelligence.

While the systems mentioned above offer continuous monitoring, they still rely on simple threshold-based alerts, which only notify healthcare providers when things go wrong. This limits their ability to detect early signs of health problems. Moreover, they lack the advanced analysis provided by fuzzy logic, which could better handle the variability and uncertainty in real-time health data. From a structural standpoint, many existing wearables fail to adequately address material fatigue from repeated bending, secure but comfortable fastening mechanisms, and the integration of sensors as embedded intelligence within the material-structure system rather than as add-on components. For example, even the machine learning-based heart rate systems don't account for important factors like SpO₂ levels, and they miss the precision that fuzzy logic offers. This leaves many current systems unable to predict health issues early and structurally unprepared for sustained daily use, which is exactly what remote monitoring systems are designed to do.

This study attempts to fill the gap left by existing systems by integrating fuzzy logic algorithms for real-time health anomaly detection into a wearable device that continuously monitors both heart rate and SpO₂ levels, while simultaneously addressing the device as a smart structural system. The aim is to propose a system capable of monitoring health parameters and, by analyzing them, predicting possible health problems and warning the user or caregiver in advance before aggravation. Importantly, this work frames the wearable bracelet not merely as an electronic device but as an integrated smart material-structure system where mechanical design, material selection, structural durability, energy efficiency, and sustainability are considered alongside algorithmic intelligence. In this work, the following goals are considered: design a wearable device with continuous monitoring of heart rate and SpO₂; develop a mobile application to present and analyze the data; implement fuzzy logic algorithms for the detection of anomalies; evaluate the mechanical performance, durability, and energy efficiency of the system; and assess the sustainability and environmental impact of the proposed solution. This system will be useful both in hospital and home environments to monitor patients wherever they are, with design features that ensure long-term reliability and minimal environmental footprint.

2. METHODOLOGY

The system consists of three key components: the wearable device, comprising an ESP32-C3 Xiao

microcontroller and a MAX30102 sensor integrated within a smart structural bracelet; and an Android mobile application. The bracelet structure is designed using flexible biocompatible polymers selected for their mechanical properties, durability, and comfort. The ESP32-C3 Xiao microcontroller acquires the readings from the MAX30102 sensor, performs signal processing of heart rate and SpO₂ levels by applying fuzzy logic, and then sends the results via Bluetooth to the mobile application. The sensor is embedded within the bracelet structure rather than simply attached, creating an integrated material-structure-intelligence system. The system displays real-time data to the user while performing fuzzy logic analysis on the ESP32-C3 Xiao microcontroller. The system is also integrated with Firebase for patient data storage, which admins can access to manage patient information. The flow of data from collection, processing, to display is shown in the block diagram (Figure 1), which highlights the key interactions between each component including the structural elements that ensure sensor stability and measurement accuracy.

2.1. Fuzzy Logic Implementation

Fuzzy logic plays an important role in processing health data provided by the MAX30102 sensor, namely

heart rate and SpO₂. It categorizes the data into several categories using fuzzy membership functions that enable it to handle uncertain or imprecise measurements. For heart rate, the algorithm utilizes three categories based on established medical standards (American Heart Association, 2020) Bradycardia, below 60 beats per minute (bpm); Normal, between 60 and 100 bpm; and Tachycardia, above 100 bpm. It classifies SpO₂ readings according to clinical hypoxemia thresholds (World Health Organization, 2021): Normal, when SpO₂ is above 94%; Mild, when SpO₂ ranges from 91% to 94%; Moderate, when it lies within the range from 86% to 90%; and Severe, when SpO₂ goes below 85%.

The fuzzy logic classification is mathematically represented as follows:

Heart Rate Classification:

If $HR < 60$ bpm \rightarrow Bradycardia (1)

If $60 \leq HR \leq 100$ bpm \rightarrow Normal (2)

If $HR > 100$ bpm \rightarrow Tachycardia (3)

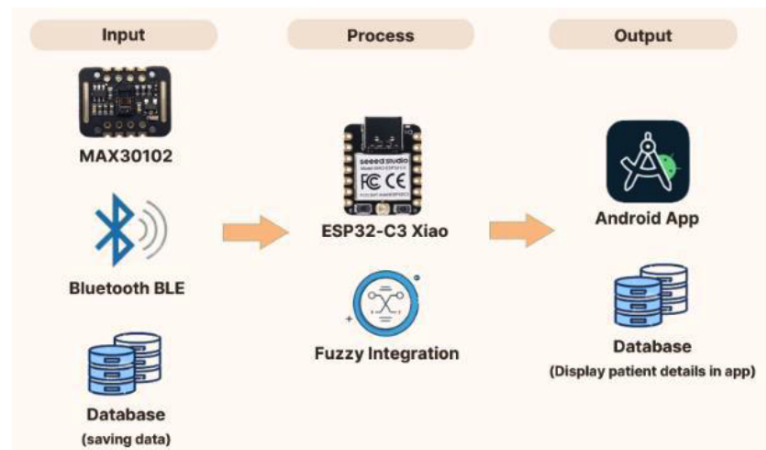


Figure 1: The schematic diagram of the health bracelet and app integration.

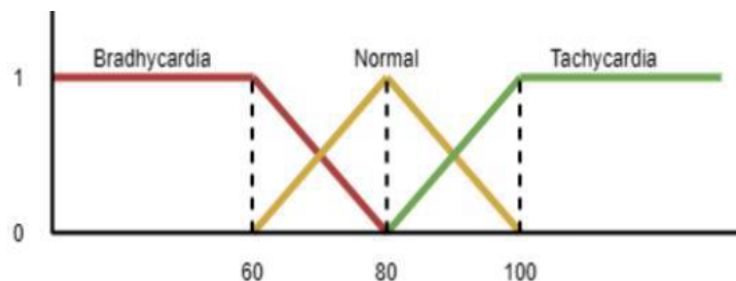


Figure 2: Heart rate fuzzy logic rules.

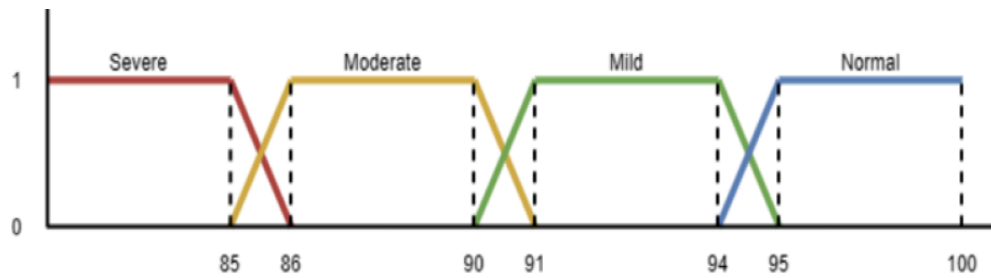


Figure 3: SpO₂ fuzzy logic rules.

SpO2	Heart rate (HR)	Prediction
Normal	Bradycardia	Normal
	Normal	Normal
	Tachycardia	Mild Hypoxemia
Mild	Bradycardia	Mild Hypoxemia
	Normal	Mild Hypoxemia
	Tachycardia	Moderate Hypoxemia
Moderate	Bradycardia	Moderate Hypoxemia
	Normal	Moderate Hypoxemia
	Tachycardia	Severe Hypoxemia
Severe	Bradycardia	Severe Hypoxemia
	Normal	Severe Hypoxemia
	Tachycardia	Severe Hypoxemia

Figure 4: Health condition fuzzy logic algorithm.

SpO₂ Classification:

- If SpO₂ > 94% → Normal (4)
- If 91% ≤ SpO₂ ≤ 94% → Mild Hypoxemia (5)
- If 86% ≤ SpO₂ ≤ 90% → Moderate Hypoxemia (6)
- If SpO₂ < 85% → Severe Hypoxemia (7)

Each of the above-mentioned categories represents ranges of values. The fuzzy logic system then considers the extent to which the data represents each category, thus providing flexibility in determining health conditions. Once the heart rate and SpO₂ data are classified, the fuzzy logic system uses rules to determine a patient's status. For example, if SpO₂ is categorized as Normal and the heart rate is Normal, the predicted health status will be classified as Normal. If SpO₂ is Mild and heart rate is Tachycardia, it could indicate Mild Hypoxemia. In case SpO₂ is Moderate and heart rate is Bradycardia, the health status can be specified as Moderate Hypoxemia. The basis for the above rules is the interaction between heart rate and SpO₂ levels for rating health status—whether it falls under categories like Mild Hypoxemia, Moderate Hypoxemia, or Severe Hypoxemia.

The result from the fuzzy logic algorithm is the health status prediction that is sent to the mobile

application. In turn, it displays all this processed data in real time, instantaneously giving users and healthcare providers insight into the patient's health status. Using fuzzy logic allows much finer evaluation of health conditions for valuable insights into better decision-making.

2.2. System Workflow

The system follows a clear, step-by-step process, as illustrated in the flowchart (Figure 5). The sequence begins with patient registration in the mobile application, which allows the admin to assign a wearable bracelet to the patient. Once the patient is registered, the admin assigns the ESP32-C3 Xiao (the wearable device) to the patient. If the bracelet is not yet assigned, the system waits for the assignment before proceeding.

Once the bracelet is assigned and worn by the patient, the MAX30102 sensor begins collecting heart rate and SpO₂ data. The collected data is sent to the ESP32-C3 Xiao microcontroller, where it undergoes fuzzy logic processing to evaluate the health status. The processed data, which includes real-time health information, is then transmitted to the mobile application via Bluetooth, where it is displayed for the user. This data is also stored in the Firebase database for future access.

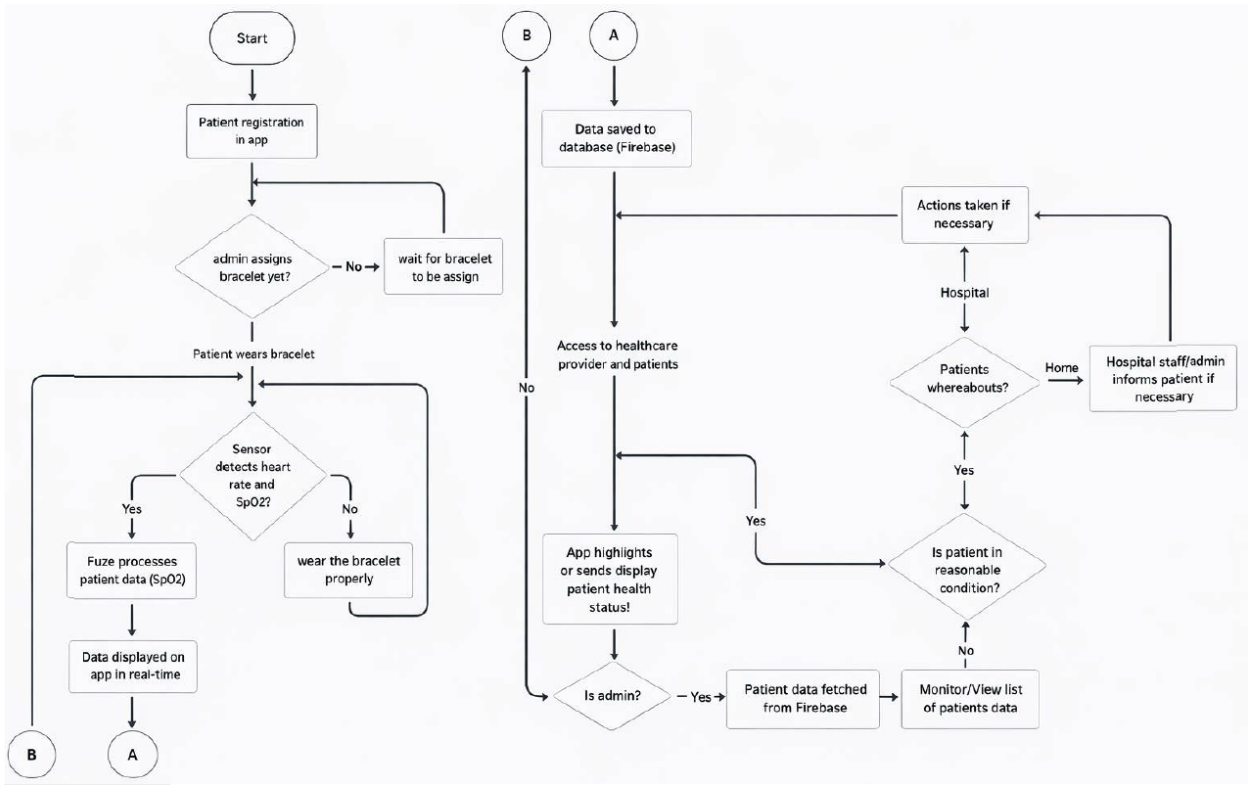


Figure 5: Health monitoring system data flowchart.

Healthcare providers and admins can access the data in the Firebase database through the application. If necessary, healthcare providers can take action based on the patient's health status, whether the patient is at the hospital or at home. This allows for continuous monitoring and management of patient health.

2.3. Hardware Configuration

The circuit diagram (Figure 6) shows the MAX30102 sensor connected with ESP32-C3 Xiao and power supply. The MAX30102 sensor receives heart rate and SpO₂ values from the user and transmits data to ESP32-C3 Xiao via I²C communication (Maxim Integrated, 2014). The ESP32-C3 Xiao processes data through fuzzy logic and transmits the processed data to mobile applications via Bluetooth Low Energy (BLE) (Seed Studio, 2023). The ESP32-C3 Xiao has a rechargeable battery with a built-in charging module. It can be easily recharged when it runs out of power. There is also a power switch provided to this unit for on/off purposes.

3. RESULT AND DISCUSSION

This section provides the results from the development and testing of the wearable health

monitoring system. It covers the fuzzy logic system used to classify heart rate and SpO₂ data, the mobile application developed to display real-time health information, and the database integration with Firebase for secure data storage and remote access. The performance and effectiveness of each component are discussed, with insights into how they work together to provide continuous health monitoring.

3.1. Fuzzy Logic System Validation

In the MATLAB environment, the fuzzy logic model, which processed heart rate and SpO₂ data, was designed and tested. First, the design of the Fuzzy Inference System (FIS) was created using the MATLAB Fuzzy Logic Toolbox. The membership functions applied to heart rate and SpO₂ levels by the fuzzy logic system categorized data into Normal, Mild Hypoxemia, Moderate Hypoxemia, and Severe Hypoxemia. Figures 7 and 8 show the tested fuzzy logic system. Once the fuzzy logic system was validated and successfully tested in MATLAB, it was then implemented on the ESP32-C3 Xiao microcontroller. The fuzzy logic algorithm developed in MATLAB for processing data in real time on ESP32 provided the foundation for classifying health conditions while receiving data from the MAX30102 sensor simultaneously.

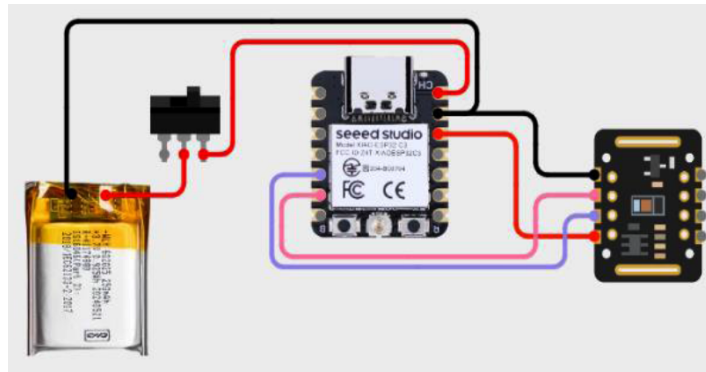


Figure 6: Circuit diagram of health bracelet.

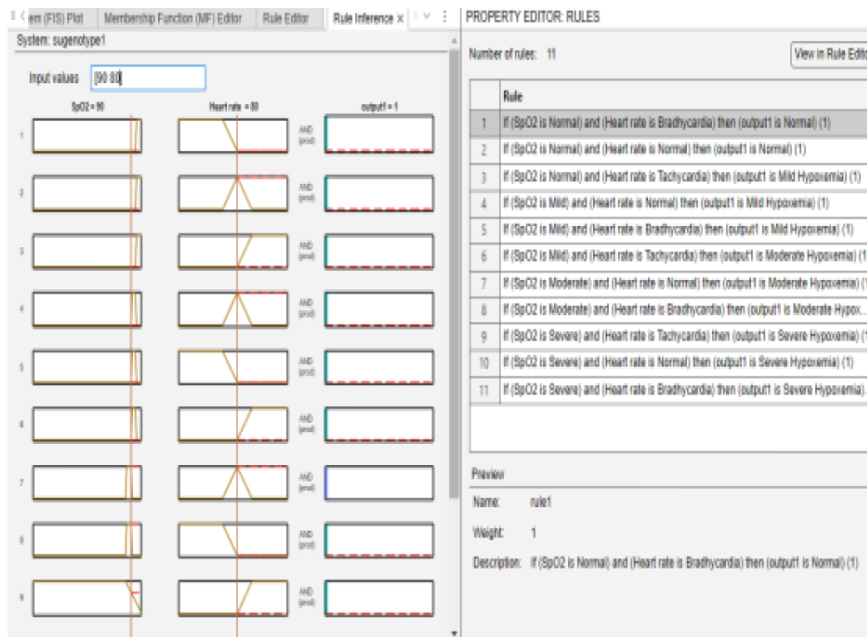


Figure 7: The fuzzy logic rule editor in MATLAB.

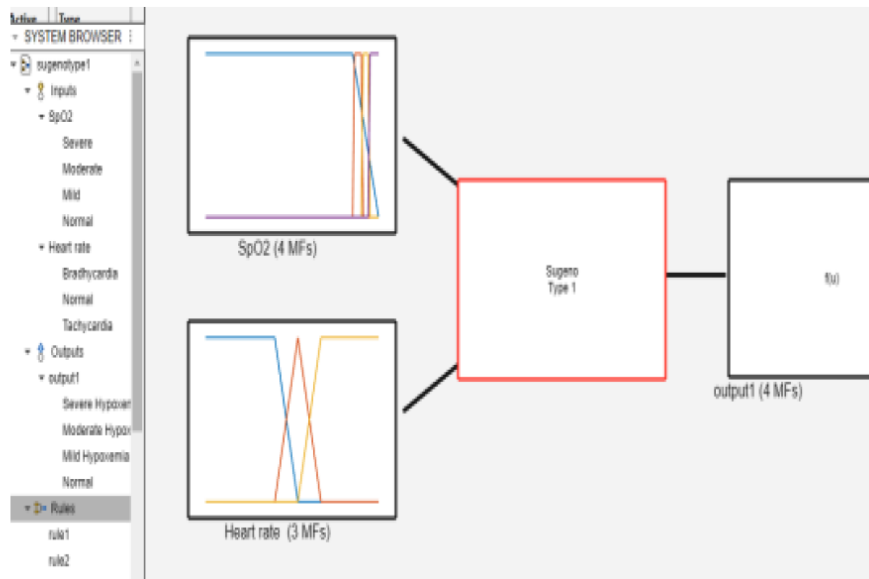


Figure 8: Fuzzy inference system.

3.2. Mobile Application Development

The mobile application acts as the central interface for all patients and healthcare providers, providing monitoring of health data in real time. It fetches health information from the Firebase database and presents it to admins (staff members).

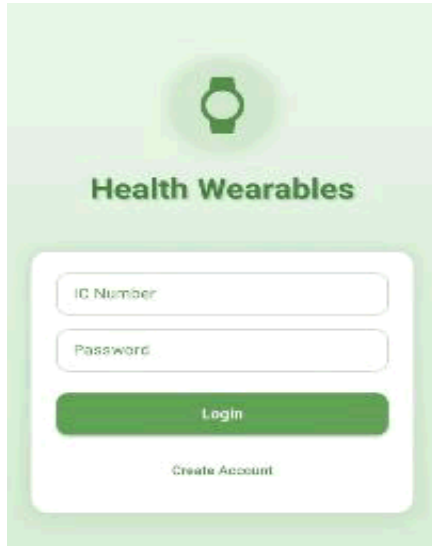


Figure 9: Login page for patients and admin login.

The login page (Figure 9) serves as the entry point for both patients and admins. Patients log in using their IC number and password. Admins, on the other hand, authenticate manually via credentials set up in the Firebase database, without requiring an IC number. For new patients, they must first create an account (Figure 10) using their Full Name, IC Number, Phone Number, Age, Gender, and Password before they can log in and

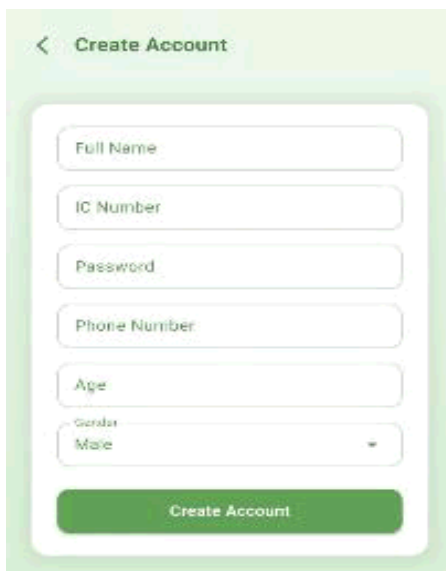


Figure 10: Registry page for patient registration.

start using the application. Once registered, the application allows access, but patients need to wait for a bracelet to be assigned. After a bracelet is assigned, the patient needs to log in and wear the assigned bracelet to view their health data (Figure 11).

3.3. Real-Time Data Transmission and Display

The MAX30102 sensor, connected to the ESP32-C3 Xiao, uses Bluetooth BLE to wirelessly transmit health data (heart rate and SpO₂) to the application. This data is displayed in real time on the Patient Health Page for patients to monitor their health status. The data is then transferred to the Firebase database to be stored. In the personal health page, patients can view their last 2 minutes of health data history after logging in (Figure 11).

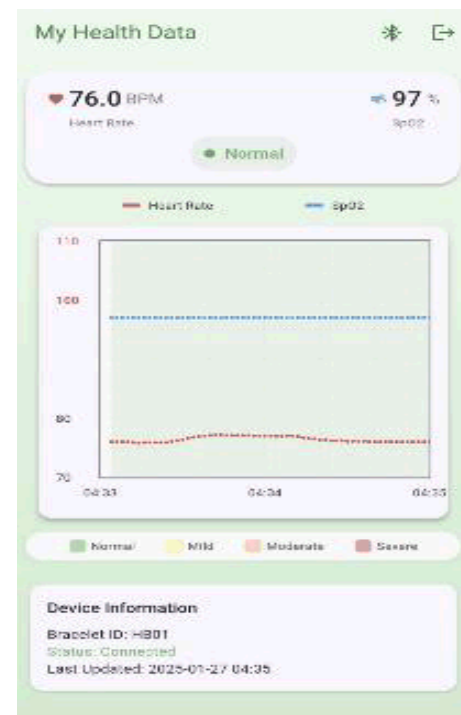


Figure 11: Personal health page.

The application provides visual feedback to patients based on their health data using a color-coded system. Fuzzy logic is used to classify the patient's health status into categories like Normal, Mild Hypoxemia, and Severe Hypoxemia. The background color changes according to the health status: green for Normal, yellow for Mild Hypoxemia, and red for Severe Hypoxemia. This real-time color-coding helps patients easily understand their health condition at a glance. Mock data is generated using ESP32-C3 Xiao to visualize health status as an example (Figure 12).

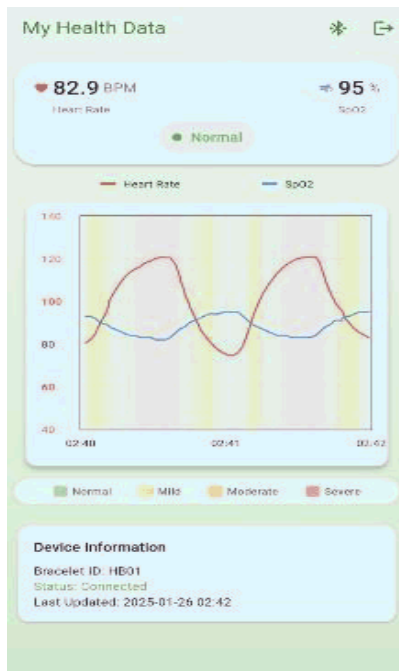


Figure 12: Personal health page (mock data for health status visualization).

3.4. Administrative Interface and Data Management

For admins, when logged in, the application retrieves patient health data from the Firebase database. The Admin Patient List (Figure 13) displays a list of patients, including their health status and bracelet ID. The application automatically fetches this data from the database and updates it in real time, ensuring that admins have access to the latest patient health information. On this page, a circular dot displays the color of the current health status of each patient.

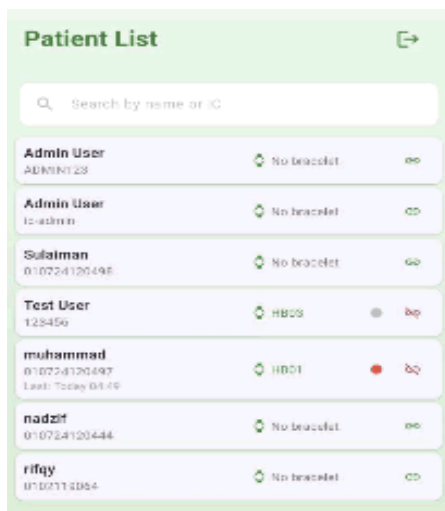


Figure 13: Admin view (patient list).

Admins can assign bracelets to patients by selecting from available bracelet IDs in the application

(Figure 14). When a patient hasn't been assigned a bracelet yet, the application will display a notification indicating the status "No bracelet assigned" (Figure 15). The screen shows a message informing the patient that they need to wait for healthcare staff to assign a bracelet to their account. When an admin clicks on a patient's name in the patient list, the application will display the patient's health data history, specifically the last 6 minutes of data, different from the patient personal health data that can only view their last 2 minutes of health data history.

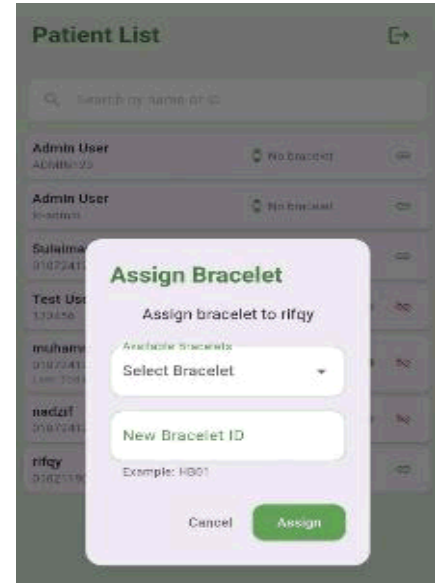


Figure 14: Admin assign bracelet.

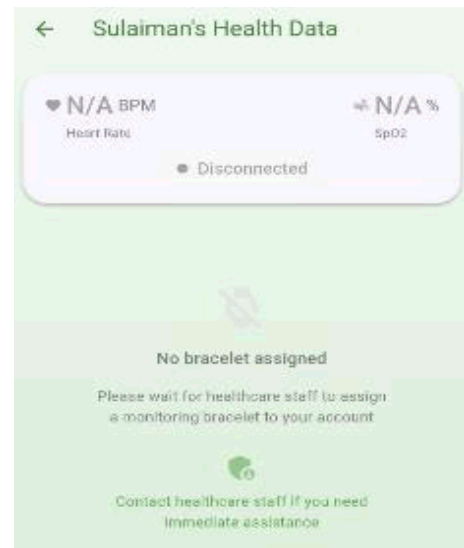


Figure 15: Patient health page when no bracelet is assigned.

3.5. Database Integration

Firestore acts as the central data storage for the application, where health data is securely stored

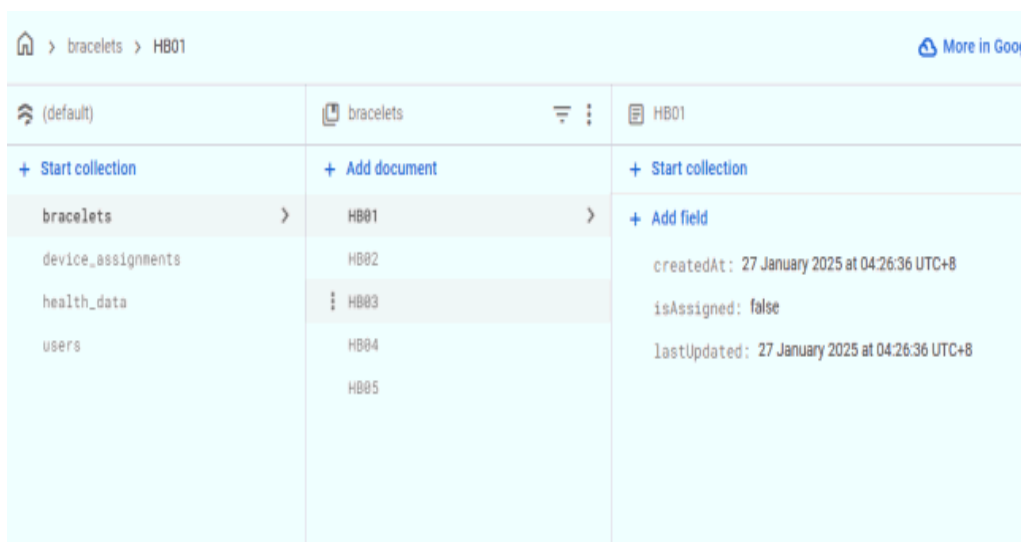


Figure 16: Firebase setup for patient information, health data, and more.

(Figure 16). The application retrieves real-time health data from Firebase and displays it in the Admin View to allow healthcare providers to monitor patients remotely. This ensures that patients are continuously monitored, and admins have access to the latest data to take necessary actions when required.

4. CONCLUSIONS

This wearable health monitoring system provides an innovative solution for continuous and real-time tracking of heart rate and SpO₂ levels. The MAX30102 sensor, interfaced with the ESP32-C3 Xiao microcontroller, enables the system to effectively collect and process health data, classifying various health conditions using fuzzy logic algorithms. The integration of Firebase further enhances the system by enabling remote monitoring, allowing healthcare providers to access patient data and intervene when necessary.

This study addresses the increasing demand for accessible and continuous health monitoring, especially among people with limited access to healthcare facilities. The system provides a practical and cost-effective solution, particularly for people suffering from chronic conditions or living in rural areas. It helps bridge the gap in healthcare accessibility by providing a reliable means for tracking vital health metrics. In summary, this wearable health monitoring system contributes to modern healthcare by providing a proactive approach to real-time health tracking.

The system is scalable and adaptive; further enhancements can be made, such as moving from a

fuzzy logic approach to artificial intelligence (AI) or machine learning (ML) algorithms. These will further enhance the system's capability in predicting health conditions more accurately as it learns from accumulated data. AI/ML will enable the system to continuously adapt to individual patient profiles for more personalized health insights. Additionally, the wearable device could be redesigned as a bracelet with Wi-Fi capability to avoid the use of a smartphone. With the introduction of Wi-Fi, the device would directly send data to Firebase or any cloud service, thereby increasing the system's autonomy and simplifying the user experience. This would make the device more convenient and user-friendly for everyday use.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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Received on 26-02-2026

Accepted on 25-03-2026

Published on 10-04-2026

<https://doi.org/10.65904/3083-3604.2026.02.03>

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