

Advancing Healthcare with IoT: Digital Twins and AI-Driven Cardiac Diagnostics

**Janaki Rani M.¹, Mohammad Kaif S K.², Gopi Chand R.³,
Ramesh D.⁴**

Department of Electronics and Communication Engineering, Dr.M.G.R Educational and Research Institute, Chennai, India.

E-mail: ¹janakirani.ece@drmgrdu.ac.in, ²skmohammadkaif13@gmail.com, ³gopirachamalla.999@gmail.com, ⁴dasariramesh5959@gmail.com

Abstract

Healthcare monitoring techniques have gone through substantial evolution over the years, and IoT coupled with Digital Twin technology represents one of the most promising ways towards providing quality healthcare services in a more patient-centric manner. In this regard, the current study proposes to design a real-time cardiac monitoring solution based on ESP32 microcontroller, AD8232 electrocardiogram sensor, MAX30100 pulse oximetry and heart rate sensor, as well as DS18B20 digital temperature sensor. Data about the vital signs will be uploaded to the cloud and used to create a Digital Twin that will be constantly updated with the new information. Healthcare specialists can interact with the digital twin to analyze historical information, run different simulations of possible health problems and come up with customized treatment strategies without having direct contact with a patient. Programming will be done in the Arduino environment, data will be stored and analyzed using Firebase Firestore, and the web application interface will use React platform. Preliminary results indicate that the suggested approach can dramatically decrease time needed to deliver a response after the abnormal cardiac condition occurs, as well as decrease in-person visit frequency required by patients from rural or underdeveloped areas.

Keywords: Digital Twin, IoT, Remote Patient Monitoring, ECG, Firebase, Healthcare.

1. Introduction

Cardiac disorders are among the leading causes of death worldwide, and a large portion of these deaths can be prevented through early detection and continuous monitoring. Traditional clinical methods depend on periodic hospital visits, which often mean that warning signs between appointments go unnoticed. With the rapid growth of embedded electronics, low-power microcontrollers, and cloud-based platforms, it has become feasible to bring continuous cardiac monitoring outside the hospital and directly to the patient.

The implementation of the Internet of Things in healthcare is meant to give power to the patients and the medical personnel through real-time monitoring of the physiological parameters using wearable and implantable sensors. The term Internet of Things means a network of physical devices with the ability of data collection and transmission that does not require human-to-human or human-to-computer communication. By applying it to the healthcare system, IoT makes it possible to obtain continuous data on vital signs including heart rate, ECG waveforms, body temperature and more.

Digital Twinning technology makes the process one more step ahead since it creates a dynamic simulation of the patient's state based on real-time data collected using sensors. Such virtual patient can be analyzed, interrogated and even be used for simulations regarding the effects of certain medicines or therapies on the state of the patient. The concept is well-known and proven for manufacturing and aerospace industries, while ours implements the idea into healthcare monitoring services.

Some of the primary factors that motivate this study are: (1) Prevention of heart attacks before they become emergencies. (2) Effective monitoring of various chronic ailments like arrhythmia, hypertension, etc. (3) Immediate clinical decision-making at any point in time irrespective of the distance between the clinician and the patient. (4) Saving costs by avoiding unnecessary hospital visits. The remainder of this paper is organized as follows. The background is discussed in Section 2. The proposed system architecture is described in Section 3. Results of experiments are presented in Section 4. Conclusion follows in Section 5.

2. Related Works

In their work, Khan et al. [1] presented a Digital Twin-enabled Internet of Robotic Things architecture for remotely monitoring COVID-19 patients. This work illustrated how

digital twins can be used in IoT-based healthcare applications. The authors' proposed architecture can be applied only to monitoring COVID-19 patients and cannot be used for other cardiac diseases or multi-parameter vital signs correlation.

The datasets on the COVID-19 Temperature, Oxygen and Pulse Rate [2] and Human Vital Signs [3] are examples of basic data sets that can be utilized to train healthcare monitoring models. They contain baseline values for temperature, oxygen saturation, and pulse rate. Although these datasets were helpful for scientific research, they should be considered offline data sources that do not cover live data collection scenarios.

Scheuermann et al. [4] introduced an application of machine learning through Digital Twins to predict individual stress in extreme conditions. While the research showed the possibility of Digital Twins in predicting individual responses and adjusting predictions according to those responses, its primary purpose was not healthcare but rather stress monitoring in industries and extreme conditions.

Gupta et al. [5] suggested a system of anomaly detection based on hierarchical federated learning using Digital Twins in smart healthcare. In order to address the problem of data privacy in healthcare applications, they used the federated learning technique, which enabled distributed learning and the creation of individual Digital Twin models for each patient. Despite the benefits of federated learning in protecting privacy, it is difficult to implement due to the complex architecture required.

Mao et al. [6] proposed a health monitoring system that employed triboelectric sensors along with intelligent Medical IoT and Virtual Reality applications. They proposed a health monitoring system that made use of innovative sensors apart from traditional sensors, such as electrodes. Despite all the innovations proposed in the design of the system, its complexities and high costs prevented it from being implemented extensively due to its high cost.

Abirami and Karthikeyan [7] designed a digital twin healthcare system that focused on identifying and diagnosing Parkinson's disease through an optimized fuzzy-based K-NN classification approach. This research proved the efficacy of digital twins in diagnosing diseases when used with effective classifiers. Although their study provided a solution to identify Parkinson's disease, the scope of their study remained limited to only identifying diseases.

Lung-DT is a digital twin-based Artificial Intelligence system introduced by Avanzato et al. [8], especially designed for thoracic monitoring and diagnosis purposes. In this research, artificial intelligence technology was coupled with Digital Twin modeling for evaluating lung health parameters as well as providing assistance for clinical diagnosis. Although their method proved to be highly accurate in diagnosing lung diseases, their solution only focused on the thoracic region and could not monitor multiple cardiac vital signs.

In addition to that, Khan et al. [9] developed a new kind of digital twin model using WiFi Channel State Information and machine learning algorithms to monitor patients' respiratory activities and provide clinical decision support. This solution does not involve using any sensors placed on the body of the patient; therefore, it provides a more comfortable monitoring experience for them. Nevertheless, WiFi-based solutions are extremely vulnerable to external interferences.

Nancy et al. [10] designed a Digital Twin framework focused on respiratory wellness and healthcare. In their research, the authors used a scalable computing solution for tackling issues related to the processing power required to monitor various patient's health parameters continuously. Although Nancy et al. [10] developed a scalable system of Digital Twins, it was dedicated only to respiratory health measurements and could not include cardiac monitoring based on multiple parameters.

The proposed system resolves the aforementioned problems by using a combination of real-time multi-parameter sensing, connection to the cloud server, the use of a Firebase-based Digital Twin model, and React web interface all supported on an affordable ESP32 hardware. It allows small-scale hospitals to implement advanced monitoring systems without significant investment costs.

3. Proposed Work

The proposed architecture uses the ESP32 microcontroller along with three biometric sensors - AD8232 ECG Sensor, MAX30100 Pulse Oximeter Sensor, and DS18B20 Digital Temperature Sensor. The collected data is transmitted to the Firebase cloud database, which forms the crux of the storage system and Digital Twin design. The patient's live and historical vitals can be viewed using a web interface built on the React framework.

3.1 System Architecture

The proposed system (as shown in Figure 1) consists of sensor components, communication, storage components for storing data in the cloud, modeling Digital Twin, and processing data to monitor heart status. This operation utilizes ECG, heart rate, and temperature sensors for receiving real-time data from the patient. This information is then processed by the ESP32 microcontroller. Subsequently, it is transmitted to the cloud via Wi-Fi connectivity for secure storage.

Within the cloud environment, the proposed solution develops a Digital Twin that models patient heart activity. The Digital Twin receives updates continually based on incoming information. The operation utilizes machine learning algorithms for analyzing such information, detecting anomalies, and making predictions about future trends.

The information acquired from data analysis is then provided to healthcare professionals and patients via a screen or dashboard. This allows them to evaluate their health status remotely and take appropriate actions. System architecture plays an integral part in monitoring, digital twin modeling and intelligent analysis are elements of the system architecture.

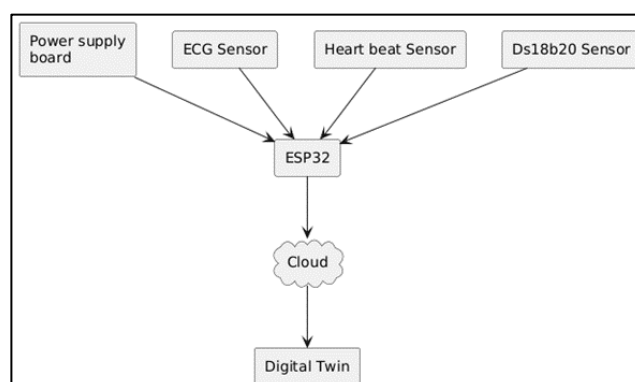


Figure 1. Architecture of the Proposed System

3.2 ESP32 Microcontroller

The ESP32 (Figure 2) is an inexpensive System-on-Chip (SoC) offered by Express if Systems that includes two cores 32-bit Xtensa LX6 CPU clocked at speeds up to 240 MHz, 520 KB of SRAM, onboard Wi-Fi 802.11 b/g/n capabilities, and Bluetooth 4.2/BLE within one package made using TSMC 40 nm technology node. Given its characteristics, it perfectly fits battery-operated, Internet-of-Things (IoT) devices. In this case, the ESP32 SoC is used as the

computing core where it collects raw data from sensors via GPIO/I²C interfaces, processes them into JSON format, and sends them to Firebase via WiFi network. Arduino development platform is utilized as a programming environment because of its vast library resources for interfacing sensors and connecting to Firebase.

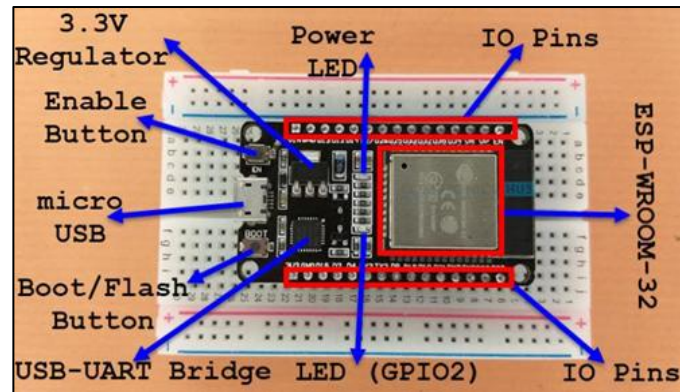


Figure 2. ESP32 Microcontroller

3.3 ECG Sensing — AD8232 Module

The electrocardiogram is a measurement of the electrical activity of the heart and is the reference method for diagnosing any heart abnormality such as arrhythmia or ST-segment changes. The reason for the choice of the AD8232 electrocardiogram (ECG) front-end integrated circuit (Figure 3) for this design is due to the inclusion of features on the device such as fully differential instrumentation amplifier, right leg drive (RLD) amplifier, uncommitted operational amplifier, and three-pole adjustable low-pass and high-pass filter on the small 4 mm x 4 mm LFCSP die. The device works on 2 V to 3.5 V power supply voltage, consumes very low current consumption of 170 μ A, and offers CMRR as high as 80 dB to eliminate the mains interference of 50/60 Hz in the recorded electrocardiograms from the home environment. This module works in both two-electrode and three-electrode modes. In our prototype three electrodes will be utilized (right arm, left arm, and right leg) to perform full RLD and obtain clean ECG waveform of one lead. The analog signal is then sent directly to one of the ESP32's ADC channels at 250 samples.

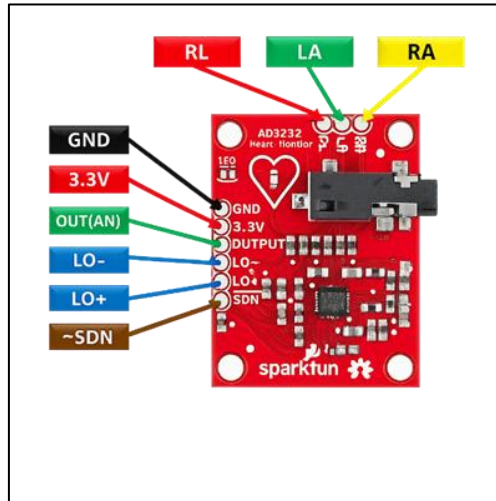


Figure 3. ECG Sensing — AD8232 Module

3.4 Heart Rate and SpO₂ — MAX30100

MAX30100 (Figure 4) is an integrated pulse oximeter/heart-rate sensor using PPG technology, which shines red (660 nm) and infra-red (880 nm) light from its LEDs and compares absorption between oxygenated and de-oxygenated haemoglobin using a photo-detector. The device has features such as Ambient Light Cancellation (ALC), 16-bit Sigma-Delta ADC, and a 16 deep FIFO. Communication between the MAX30100 and the ESP32 is done using an I²C interface having address 0x57 and needs just 1.8 V digital power and 3.3 V LED power. The very low consumption of maximum 0.7 μ A in shutdown mode makes it ideal for use in wearables and battery-powered devices. MAX30100 gives us the values of the heart rate (BPM) and SpO₂ (%) in addition to ECG in our system at intervals of five seconds.

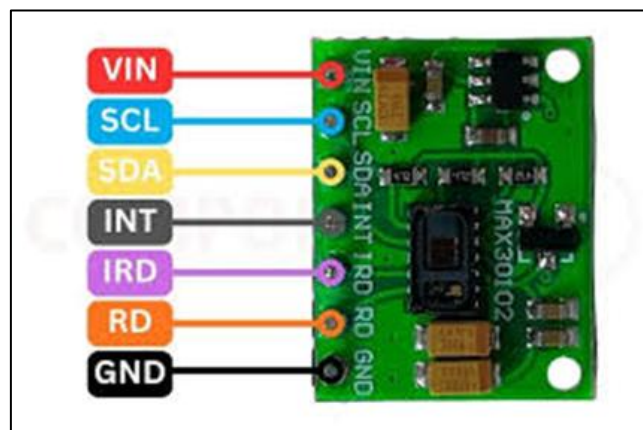


Figure 4. Heart Rate and SpO₂ Module — MAX30100

3.5 Temperature Sensing — DS18B20

Fever serves as a valuable additional marker in cases of cardiac events since it increases heart rate and can either conceal or aggravate arrhythmias. The DS18B20 (Figure 5) is a digital thermometer that employs a 1-Wire interface with 64-bit ROM for addressing, configurable resolution ranging from 9 to 12 bits, and $\pm 0.5^{\circ}\text{C}$ accuracy across temperatures between -10°C and $+85^{\circ}\text{C}$. The sensor does not require its own power supply; instead, it uses parasite power derived from the signal line. Therefore, only one resistor pull-up device and one GPIO pin on the ESP32 are required for operation. The One Wire and Dallas Temperature Arduino libraries manage the timing of protocol communication, which enables obtaining the temperature values using a minimal amount of code.

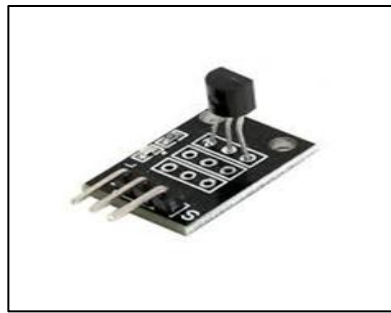


Figure 5. Temperature Sensing Module — DS18B20

3.6 Digital Twin Architecture

Digital Twin represents an online data representation of the patient's current physiology status. For this purpose, Firebase Cloud Firestore has been selected as the data persistence layer since it allows to keep records of the patient's information in form of NoSQL document storage with the possibility of scaling and providing real-time listeners which enable instant data retrieval after a new event occurs, i.e., there is no polling required. Each document in Firestore corresponds to one patient and comprises several collections containing records of ECG data, SpO₂/HR measurement values, and temperatures. Shallow queries provided by Firestore make possible fetching only the last 100 ECG entries from the history instead of fetching the whole record. Authorization of access is guaranteed by Firebase Auth where patients and clinicians can enter into Firestore using the Email/Password provider. Firestore Security Rules ensure that patients can read only their own record while registered clinicians are allowed to read any record in their ward. Firebase Cloud Messaging (FCM) allows sending push notifications on the heart rate above 120 bpm, SpO₂ lower than 94%, or detected arrhythmia.

Algorithm 1: AI-Driven Digital Twin Cardiac Monitoring System

Input: Sensor data: ECG, Heart Rate (HR), SpO₂, Temperature

Output: Real-time monitoring, anomaly detection, and alert generation

- 1: Initialize sensors (AD8232, MAX30100, DS18B20)
 - 2: Establish Wi-Fi connection using ESP32
 - 3: Connect to Firebase Cloud Database
 - 4: while system is active do
 - 5: Acquire physiological signals from sensors
 - 6: Perform preprocessing:
 - 7: Remove noise from ECG signals
 - 8: Normalize sensor data
 - 9: Extract features (HR, RR interval)
 - 10: Convert processed data into JSON format
 - 11: Transmit data to Firebase cloud
 - 12: Update Digital Twin model:
 - 13: Synchronize real-time patient data
 - 14: Store historical records
 - 15: Apply AI-based analysis:
 - 16: if abnormal patterns detected then
 - 17: Classify condition (e.g., arrhythmia, hypoxia, fever)
 - 18: else
 - 19: Continue normal monitoring
 - 20: end if
 - 21: Perform predictive analysis using time-series model
 - 22: Update real-time dashboard visualization
 - 23: if threshold limits exceeded then
 - 24: Trigger alert using Firebase Cloud Messaging (FCM)
 - 25: end if
 - 26: end while
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4. Results and Discussion

The prototype was developed using a universal PCB that featured ESP32 DevKit V1 (30-pin version) as its main module. AD8232 was interfaced using snap electrodes with a 3.5

mm connector positioned in the usual three-electrode arrangement. MAX30100 breakout board was interfaced using a small plastic housing on the fingertip of the patient. Temperature data acquisition was done using DS18B20 sensors that were taped around the wrist region of the patient to measure the skin temperature. The complete device was fed with power from a 3.7 V 1500m Ah Li-Po battery using a 3.3V regulator (AMS1117).

The experimental testing involving five healthy individuals, the ECG waveforms presented on the React dashboard were visually similar to the results observed in standard Lead I ECGs acquired using a clinical grade apparatus acting as the reference point. The heart rate values determined by the MAX30100 sensors were off the reference finger clip pulse oximeter value by 2 bpm on average, and the SpO₂ values were accurate up to $\pm 1\%$, when the measurement was between 95% and 100%. Temperature measurements carried out via the DS18B20 sensors corresponded with those of a calibrated digital thermometer to within 0.4°C. In terms of the delay from when a sensor detects an event until the corresponding change occurs on the dashboard, a mean value of 340 ms was measured over a standard home broadband network, which is sufficiently acceptable for applications in cardiac monitoring systems where near real-time updates are expected. Push notifications using the FCM service sent to the Android test device from the time when the threshold is breached was received under two seconds on average.

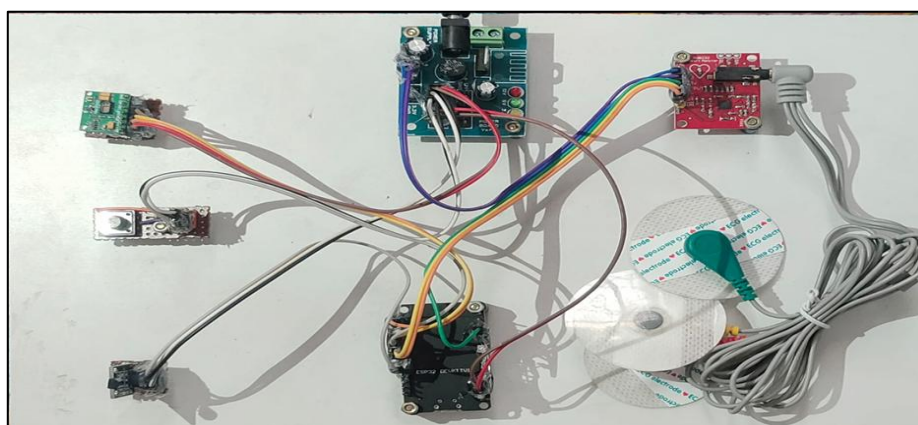


Figure 6. Experimental Setup of IoT-based Patient Monitoring System

Figure 6 illustrates the hardware arrangement of the IoT-based patient monitoring system that is being proposed. In this case, the core of the system is an ESP32 microcontroller which interfaces with a number of sensors. For instance, the heart and SpO₂ level data collection is done using the MAX30100 sensor. The DS18B20 sensor collects temperature data from the body. On the other hand, the heart rhythm is measured through the AD8232 ECG

module together with the electrode pads. A power supply is used to supply voltage to the entire set up.

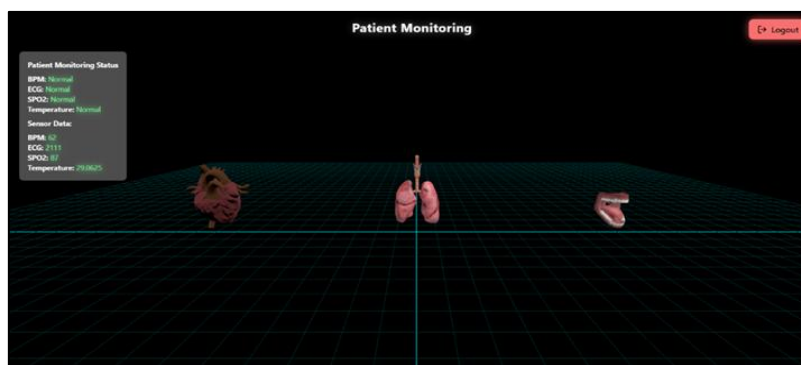


Figure 7. Patient Monitoring

Figure 7 depicts the interface created for real-time patient monitoring using a digital twin model that allows users to view the patient's physiological parameters obtained from IoT devices. The left side shows the status of monitoring of some essential vital signs, including heart rate (BPM), ECG, SpO₂, and body temperature along with the live data being provided by the sensors. The middle area represents a virtual 3D model of the human organs, such as heart and lungs placed in a grid-based model simulating the current state of the patient. This combination of live physiological data with the virtual model helps in achieving continuous remote monitoring. The user can log out of the system through the logout button provided.

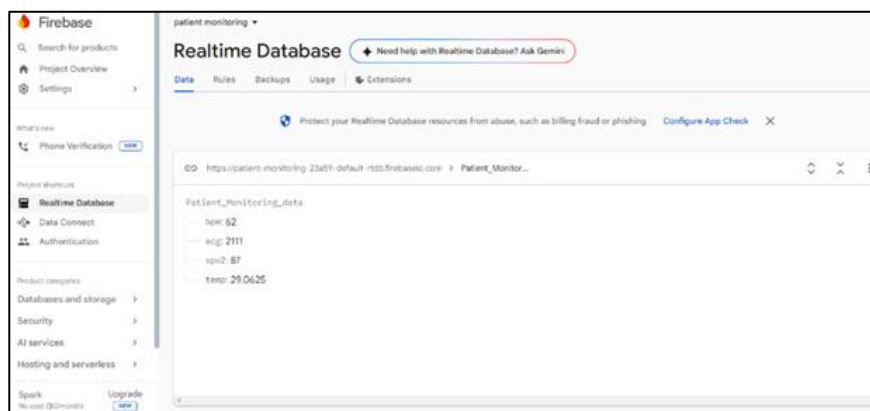


Figure 8. RealTime Database

Figure 8 represents the Firebase Realtime Database, which acts as a storage medium for the real-time patient data. The database includes a structured node named 'Patient Monitoring data', where the physiological parameters like Heart Rate BPM, ECG, SpO₂ (Blood Oxygen Saturation) Level, and Temperature are updated real-time. All these parameters have been stored under key-value pairs in the database, providing an efficient means of

communication between the IoT-based sensing system and cloud computing platforms. Using real-time databases enables low latency data transmission, making it easier to update the digital twin dashboard in real time.

5. Conclusion

This research has developed a low cost, internet connected remote cardiac monitoring system using IoT sensors integrated with Digital Twin technology. The ESP32 hardware node measures ECG, heart rate, SpO₂ level, and body temperature and uploads the measurements to the backend Firebase Firestore where the Digital Twin model specific to each patient is updated in real time. The clinician is provided a React-based dashboard which displays patient vitals, past trends, and sends instant FCM notification if any reading exceeds normal levels. Experimental results showed that the system has achieved the same sensor accuracy as that of the reference devices used clinically, with a latency time of less than 400 milliseconds and notifications within 2 seconds of crossing the threshold value. The total cost of building the entire hardware per patient is less than 35 US dollars, thus making it suitable for rural healthcare programs as well as remote locations where cardiac monitoring was not feasible earlier. Future development would include the development of a machine learning model for arrhythmia detection using on-board inference capabilities of ESP32 chip through Tensor Flow Lite. Additionally, LoRaWAN communication support will be added to this project to address lack of WiFi connections in certain areas.

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