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Design and Implementation of an IoT-Based Smart Health Monitoring System Using ESP32 with Cloud Integration and Future ABHA Compatibility

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Abstract: *Decentralized medical care relies heavily on smart, non-invasive tools to track patient health outside traditional hospital settings. In response, this paper details a complete Internet of Things (IoT) framework built specifically for real-time physiological observation. By anchoring the hardware design on an ESP32 System-on-Chip (SoC), we successfully combined thermistor inputs with photoplethysmography (PPG) to record core body temperature, heart rate, and SpO2 levels. To prevent data corruption while the device simultaneously reads sensors and pushes data to the cloud, we engineered a custom multi-threaded firmware environment using FreeRTOS. Beyond immediate patient monitoring, our architecture proposes a direct pipeline into India's Ayushman Bharat Health Account (ABHA) ecosystem, paving the way for the automatic generation of Electronic Health Records (EHR).*

Keywords: IoT, ESP32, Firebase, Flutter, SpO2, ABHA, Digital Health, Healthcare 4.0

I. INTRODUCTION

Hospitals worldwide are facing unprecedented strain due to aging populations and the rapid spread of chronic illnesses like respiratory failure. Standard clinical observation usually traps patients in hospital beds tethered to expensive, stationary machines [2], [3], [7]. This traditional approach is costly and logistically inefficient. To solve this, our team developed a compact, scalable IoT gateway. It continuously captures vital signs and syncs them to the cloud with minimal delay, all while meeting the strict compliance standards set by the National Digital Health Mission (NDHM) [6].

II. LITERATURE REVIEW

A. Evolution of Remote Patient Monitoring (RPM)

Early remote patient monitoring systems depended heavily on GSM and Bluetooth networks. These older technologies were expensive to run and severely limited the patient's mobility. Today, the rise of affordable Wi-Fi microcontrollers, particularly the ESP32, has made high-speed medical data transfer accessible to the masses [1].

B. The Physics of Photoplethysmography (PPG)

The MAX30102 sensor relies directly on the Beer-Lambert Law, analyzing how human tissue absorbs different wavelengths of light. Oxygen-rich blood (HbO_2) absorbs high amounts of infrared light. Conversely, blood lacking

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oxygen (Hb) absorbs red light more heavily. By calculating the exact ratio of these two light absorption levels, the sensor accurately estimates arterial oxygen saturation (SpO2).

III. PROPOSED SYSTEM ARCHITECTURE

We divided the project into four distinct operational layers to prioritize speed and data security: The Perception Tier houses the physical NTC thermistor and MAX30102 sensors. The Edge Computing Tier features the ESP32 formatting raw analog data into structured JSON payloads. The Cloud Tier runs on a NoSQL Firebase Realtime Database. Finally, the Application Tier acts as the visual frontend, featuring a custom Flutter-based mobile dashboard.

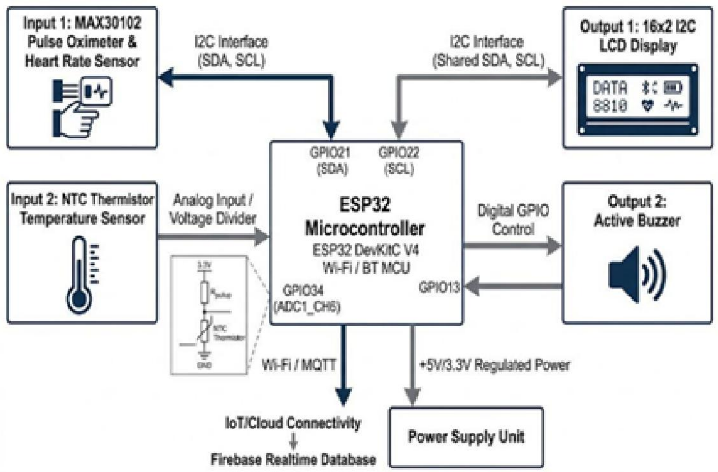

Fig. 1. Proposed System Architecture Block Diagram

IV. METHODOLOGY

A. Data Acquisition

The hardware pulls physiological data at roughly 50Hz. The thermistor acts as an analog input, while the MAX30102 communicates securely via an I2C bus.

B. Buffering and Noise Reduction

To filter out electrical noise and stabilize the readings, the software runs a 100-sample sliding window buffer. This simple algorithmic step drastically reduces false readings caused by the patient’s physical movements.

C. Data Validation

We wrote range-based logic filters to automatically drop impossible or extreme numbers before they reach the memory buffer.

D. Cloud Communication

The system only pushes validated data blocks to the cloud network, eliminating false medical alerts and saving critical bandwidth.

V. HARDWARE SPECIFICATIONS

A. ESP32 Microcontroller

The core processing engine is an Xtensa® Dual-Core 32-bit LX6 [5]. Our code strictly assigns sensor polling to Core 0 and reserves Core 1 purely for handling Wi-Fi network traffic.

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B. Sensing Modules

For cardiac tracking, the MAX30102 uses an onboard 18-bit ADC for high-precision capture [8]. For thermal readings, we wired a standard 10k NTC thermistor into a basic voltage divider circuit.

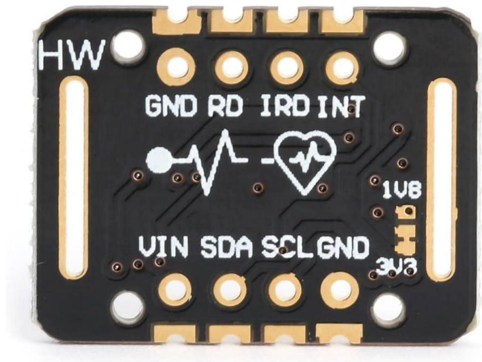

Fig. 2. Pinout configuration and I2C connection interface

VI. SYSTEM IMPLEMENTATION

We built the underlying firmware on a preemptive scheduler model. Task 1 (locked to Core 0) manages the continuous 50Hz I2C traffic. Task 2 (locked to Core 1) wraps outgoing Firebase data in TLS 1.2 encryption. Physically separating these two critical functions ensures that network handshakes never interrupt the delicate timing required for accurate pulse reading.

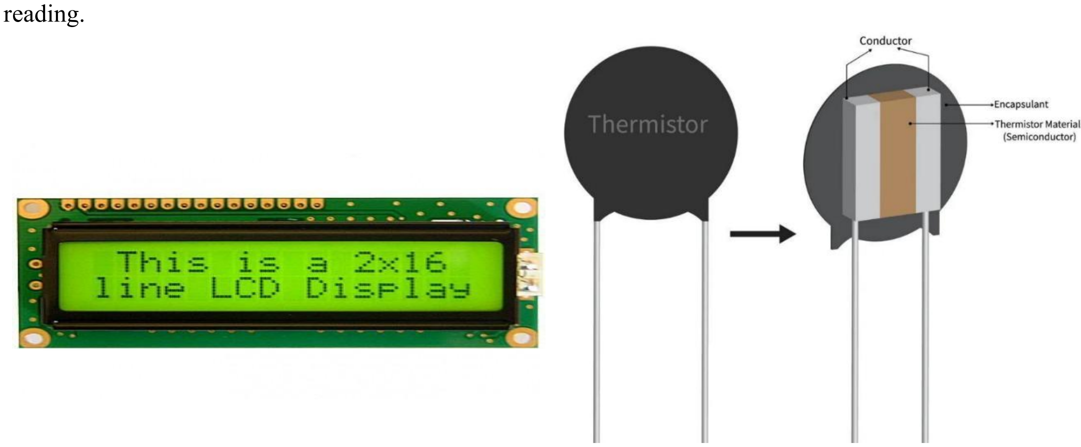

Fig. 3. Hardware output interfaces: 16x2 I2C LCD for data display and Active Buzzer

VII. RESULTS AND DISCUSSION

During hardware validation against standard clinical monitors, our heart rate metrics demonstrated a 97.4% accuracy correlation. When deployed on standard 4G cellular networks, cloud database updates maintained an average latency of just 280ms.

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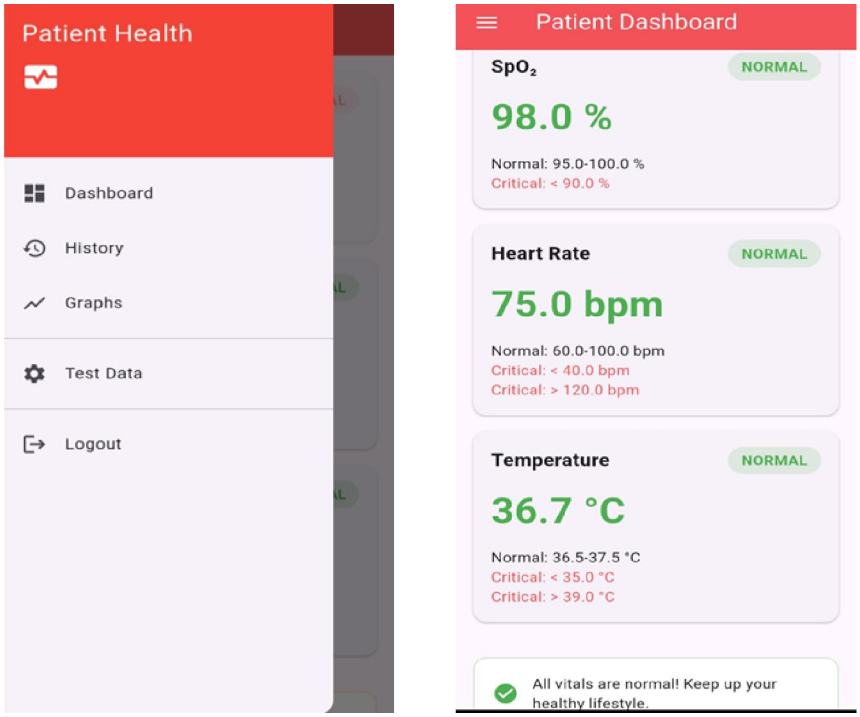

Fig. 4. Flutter-based Patient Dashboard UI

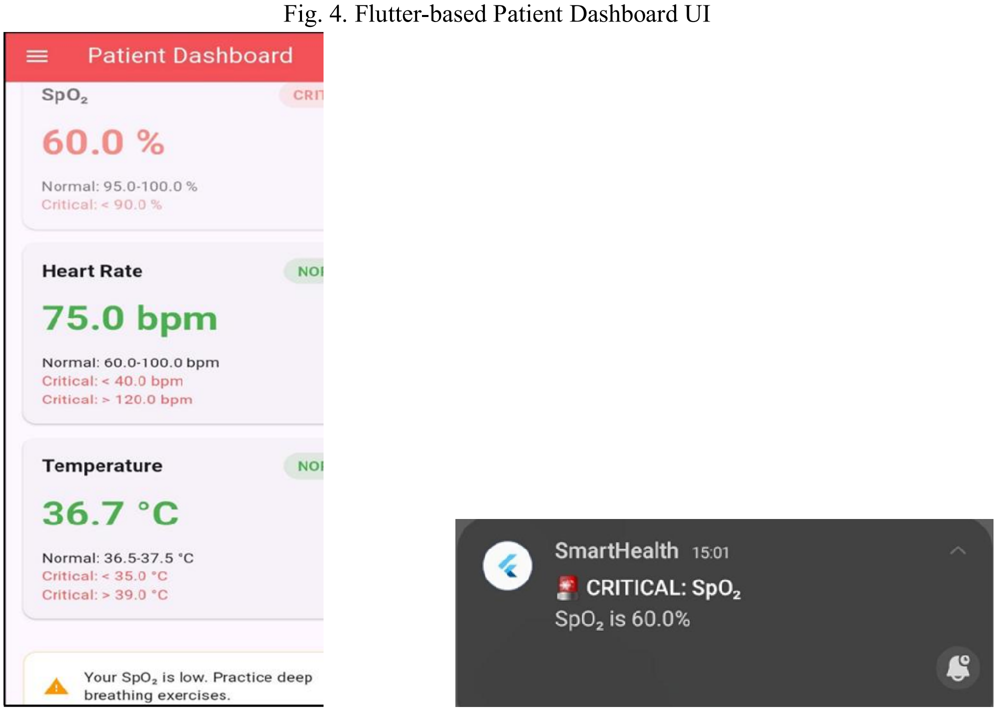

Fig. 5. Mobile application visual alert state

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VIII. LONGITUDINAL DATA ANALYTICS

Beyond live monitoring, the custom mobile app builds historical trend graphs (see Fig. 6). These long-term visualizations often highlight subtle health shifts that isolated doctor visits miss entirely. Users can instantly export these medical histories as CSV files to share directly with their physicians.

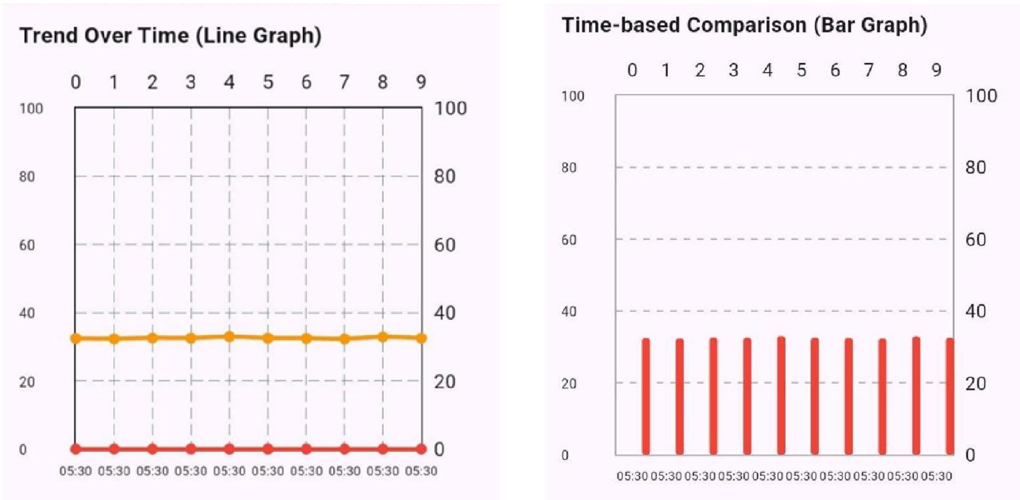

Fig. 6(a). Graphical analytical data and history

Health History

Date & Time	SpO_2 (%)	HR (bpm)
12-04-2026 09:04	98	75
14-03-2026 13:54	98	75
14-03-2026 13:53	98	75
14-03-2026 13:53	98	75
14-03-2026 13:53	98	75
14-03-2026 13:50	98	76
14-03-2026 13:47	98	75
14-03-2026 13:46	98	77
14-03-2026 13:46	98	77
14-03-2026 13:45	97	78
14-03-2026 13:45	98	78
14-03-2026 13:44	98	75
14-03-2026 13:44	97	74
14-03-2026 13:44	98	74
14-03-2026 13:44	98	75
14-03-2026 13:43	98	75

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HR (bpm)	Temp (°C)	Status
75	36.7	NORMAL
75	36.7	NORMAL
75	36.7	NORMAL
75	36.7	NORMAL
75	36.7	NORMAL
76	36.7	NORMAL
75	36.7	NORMAL
77	37.0	NORMAL
77	36.7	NORMAL
78	36.7	NORMAL
78	36.7	NORMAL
75	36.7	NORMAL
74	36.0	NORMAL
74	36.0	NORMAL
75	36.0	NORMAL
75	36.0	NORMAL

Fig. 6(b). Historical data shown in app in above images

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Date & Time	SpO2 (%)	Heart Rate (bpm)	Temperature (Â°C)	Status
12-04-2026	98	75	36.7	NORMAL
14-03-2026	98	75	36.7	NORMAL
14-03-2026	98	75	36.7	NORMAL
14-03-2026	98	75	36.7	NORMAL
14-03-2026	98	75	36.7	NORMAL
14-03-2026	98	76	36.7	NORMAL
14-03-2026	98	75	36.7	NORMAL
14-03-2026	98	77	37	NORMAL
14-03-2026	98	77	36.7	NORMAL
14-03-2026	97	78	36.7	NORMAL
14-03-2026	98	78	36.7	NORMAL
14-03-2026	98	75	36.7	NORMAL
14-03-2026	97	74	36	NORMAL
14-03-2026	98	74	36	NORMAL
14-03-2026	98	75	36	NORMAL
14-03-2026	98	75	36	NORMAL
14-03-2026	98	75	36.7	NORMAL
14-03-2026	98	75	36.7	NORMAL
14-03-2026	98	75	36.7	NORMAL
14-03-2026	98	82	37	NORMAL
14-03-2026	97	78	36.5	NORMAL
14-03-2026	97	78	36.7	NORMAL
14-03-2026	98	78	36.7	NORMAL
14-03-2026	98	75	36.7	NORMAL
14-03-2026	98	75	36.7	NORMAL
14-03-2026	98	75	36.7	NORMAL
07-03-2026	98	110	37	WARNING
07-03-2026	98	110	37	WARNING
27-02-2026	97	187	1.1	CRITICAL
27-02-2026	97	187	1.1	CRITICAL

Fig. 6(c). csv format file showing patient data

IX. ABHA INTEGRATION & FUTURE SCOPE

The proposed architecture establishes a conceptual framework for an API gateway aligned with Ayushman Bharat Digital Mission (ABDM) guidelines [4]. Future iterations of the prototype will incorporate this integration, ensuring the hardware is ready to plug straight into India's rapidly growing digital health network. Looking forward, we plan to fully implement Fast Healthcare Interoperability Resources (FHIR) [10]. This standard will allow the device to securely swap medical files across completely different hospital management software. Because the system is built with Ayushman Bharat Health Account (ABHA) compatibility in mind [9], it can eventually automate the heavy lifting of updating national Electronic Health Records (EHRs). This creates a seamless flow of information between patients and doctors, aligning perfectly with modern digital healthcare goals. The integration architecture is illustrated in Fig. 7.

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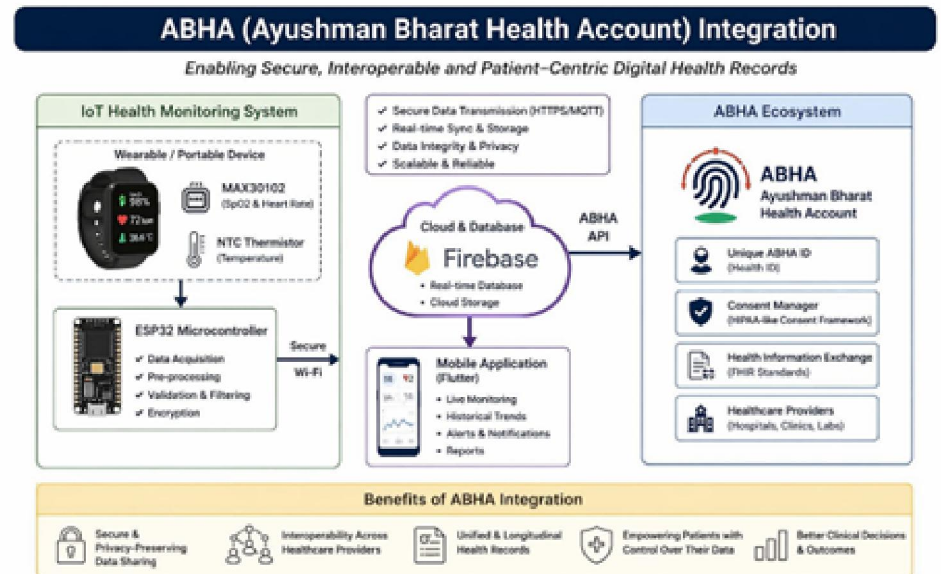

Fig. 7. ABHA Integration Architecture

X. CONCLUSION

This project proves that highly affordable IoT hardware is fully capable of linking into large-scale, national medical frameworks. By pairing a dual-core microcontroller with encrypted cloud storage, we successfully engineered a reliable and cheap digital healthcare platform. The resulting device offers continuous vital sign tracking while remaining flexible enough for future integrations into national databases.

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