Vitalmesh: Smart Clothing for Health Monitoring

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***Abstract*— Wearable health monitoring device that enables continuous, real-time vital tracking, supporting early detection, personalized care, improved safety in high-risk environments, reduced healthcare costs, and better health outcomes. Existing wearable health devices typically monitor single parameters and lack integration with real-time alerting systems for high-risk populations. This paper presents VitalMesh, a multi-sensor smart textile platform that integrates electrocardiogram (ECG), galvanic skin response (GSR), inertial measurement unit (IMU), GPS, and environmental sensors into a washable garment for continuous health monitoring. The system employs a Raspberry Pi as the computational core, interfacing with multiple sensors. Data is transmitted to a cloud-based Firebase infrastructure using Wi-Fi. The embedded system achieves seamless latency from sensor acquisition to cloud database entry, with 4+ hours of battery life on a 1000 mAh LiPo battery. A LoRaWAN communication system is used for deployment scenarios lacking reliable internet infrastructure. Security is implemented through scrypt password hashing, and role-based access control via Firebase Security. Two deployment scenarios are validated: (1) remote patient monitoring for chronic disease management with real-time cardiac anomaly detection, and (2) military personnel tracking with heat stress detection and long-range LoRa communication. The prototype demonstrates multi-parameter monitoring at a low component cost positioning VitalMesh as a scalable platform bridging consumer wearables and medical-grade devices.**

Keywords: Wearable health monitoring, IoT sensors, LoRaWAN, Firebase, ECG, smart textiles, remote patient monitoring, embedded systems

I. Introduction

The VitalMesh project addresses a critical global health challenge: the burden of non-communicable diseases, which cause 71% of global deaths and make continuous monitoring essential [1]. While the market for wearable sensors is experiencing strong growth, with a projected market size of USD 10.54 Billion in 2030 and a significant global projected growth (see Fig. 1), existing solutions often fall short of meeting comprehensive user needs [2].

VitalMesh addresses these limitations through a smart-textile "second-skin" approach that integrates multiple complementary sensors [3][4] — ECG, galvanic skin response (GSR), inertial motion (IMU), GPS, and environmental temperature — into a wearable garment [5]. Rather than relying on a single metric, the system combines physiological and contextual signals to provide a richer, real-time profile of the user [5][6]. Figures 2 and 3 illustrate the proposed wearable integration strategy: Fig. 2 presents the sensor placement layout on the garment, and Fig. 3 shows the implemented prototype with the embedded modules attached to the textile in a configuration designed to preserve mobility and comfort during continuous monitoring.

Figure 1. Projected growth of the global wearable sensors market to 2030. [2]

To support real-world deployment, VitalMesh is designed for two operational contexts: (i) healthcare monitoring, where data is transmitted with low latency to a cloud backend for remote access by caregivers, and (ii) military or remote environments, where long-range communication enables operation when conventional internet connectivity is unavailable [4][6]. By combining multi-sensor fusion, practical wearable integration (Figs. 2 and 3), and scalable connectivity aligned with the growing market need (see Fig. 1) [1][2][7], VitalMesh aims to bridge the gap between consumer wearables and specialized medical-grade monitoring platforms.

A. VitalMesh design goals and objectives

The primary objective of this research is to design, validate, and prototype VitalMesh, a scalable, multi-modal wearable system that bridges the gap between consumer-grade fitness trackers and clinical medical devices. While consumer wearables often lack medical precision and clinical devices lack comfort for daily use, VitalMesh aims to provide a "second-skin" platform that ensures clinical-grade data reliability without compromising user mobility or comfort.

To ensure versatility, the system is architected to address two distinct operational requirements:

Proactive Healthcare Monitoring: Enabling long-term, continuous surveillance of elderly patients and individuals with chronic non-communicable diseases. By transitioning from reactive to proactive care, the system facilitates early anomaly detection and remote access for caregivers via real-time cloud connectivity.

Figure 2. Sensor placement diagram for health monitoring.

Figure 3: Prototype sensor placement for health monitoring.

Personnel Health Condition Tracking in High-Risk Environment: Supporting military personnel and first responders operating in rural/remote environments. This requires robust physiological tracking (stress, fatigue, vital signs) and geolocation capabilities that function independently of standard cellular or Wi-Fi networks.

To achieve this, the research focuses on three core technical objectives:

- **Development of an Integrated Multi-Sensor Platform**

To engineer a "second skin" smart textile that seamlessly integrates heterogeneous sensors (ECG, GSR, IMU, GPS, and temperature) without compromising user mobility. A key design requirement is ensuring the system is durable, lightweight, and capable of withstanding daily wear and washing cycles (via detachable electronics) while maintaining signal integrity comparable to clinical monitors.

- **Implementation of Dual-Mode Communication**

To establish a robust communication architecture capable of operating in diverse network environments. This involves implementing a hybrid transmission protocol that utilizes Wi-Fi (IEEE 802.11) for high-bandwidth telemetry in healthcare settings and switches to LoRaWAN for long-range, low-power transmission in rural/remote areas (e.g., military fields), ensuring continuous data acquisition regardless of cellular coverage.

- **End-to-End Security and Privacy**

To address the critical sensitivity of medical data by implementing security-first architecture. The objective is to ensure confidentiality and integrity through Transport Layer Security (TLS) for data in transit, strict Role-Based Access Control (RBAC) for database interactions [8][9], and local edge-storage capabilities to preserve user autonomy and data availability during network outages.

II. RELATED WORK

The emerging market for smart clothing and wearable health devices includes several established products that integrate biosensors into textiles. These systems serve as critical benchmarks for the VitalMesh project, offering insights into current capabilities regarding functionality, accessibility, and cost.

A. Specialized Medical Monitoring

Siren Socks exemplify the integration of medical-grade sensors into everyday apparel. As an FDA-registered device for patients with diabetes and neuropathy, they continuously monitor foot temperature to detect early signs of inflammation, with clinical evidence suggesting a reduction in diabetic ulcers by up to 87%. While the system is highly effective for its specific use case and features a user-friendly, washable design, its utility is constrained by a narrow focus on temperature tracking. Furthermore, its reliance on a prescription-based subscription model limits direct-to-consumer accessibility and broader market adoption [10].

B. Athletic Performance Tracking

In the domain of fitness and athletics, Sensoria Smart Socks utilize embedded pressure sensors to monitor gait metrics such as cadence, foot landing technique, and impact forces. By coupling the textile with a core module, the system provides real-time "heat-map" feedback via a mobile application to aid in injury prevention. Although innovative, the requirement for a bulky external ankle cuff for data processing presents a design limitation regarding user comfort and aesthetics. Additionally, the relatively high cost of the kit (~$200) restricts its accessibility primarily to the serious athletic market [11].

Similarly, the CardioSport Smart BioVest offers a streamlined solution for cardiac monitoring by integrating heart rate sensors directly into a compression vest. This design eliminates the discomfort of traditional chest straps by using fabric-embedded electrodes to maintain consistent skin contact. While the BioVest is significantly more affordable (~$55) than its competitors, its functionality is limited strictly to heart rate data, lacking the multi-sensor fusion required for comprehensive health surveillance [12].

C. Comprehensive Biometric Garments

Hexoskin Smart Shirts represent a more holistic approach, embedding sensors to track a wide array of metrics including heart rate, breathing rate, activity levels, and sleep quality. These garments provide detailed biometric data suitable for research and high-level training, with extended battery life and recording capacities. However, the system presents a high barrier to entry with a cost of approximately $500, plus additional subscription fees for advanced analytics. Users have also reported challenges with the mobile application interface and sizing issues that can compromise sensor alignment and data accuracy [13].

D. Synthesis

Existing solutions highlight a gap in the current market: devices are either highly specialized and expensive (Siren, Hexoskin) or affordable but limited in scope (CardioSport). VitalMesh aims to address this disparity by offering a multi-modal, cost-effective platform that integrates clinical-grade sensors (ECG, GSR, IMU, GPS, Temperature) into a comfortable and accessible form factor, suitable for both chronic disease management and high-risk operational environments [4][5].

III. SYSTEM ARCHITECTURE AND OPERATIONAL METHODOLOGY

The VitalMesh platform is architected as a modular, layered IoT system designed to operate reliably in heterogeneous network environments. To address the divergent requirements of the two primary use cases—urban healthcare monitoring and remote military operations—the system topology is bifurcated into two distinct operational modes: the Direct-to-Cloud Healthcare Mode and the Gateway-Mediated Military Mode.

A. Healthcare System Topology (Direct-to-Cloud)

In the healthcare configuration, targeted at elderly patients or individuals with chronic conditions (e.g., arrhythmia), the system prioritizes low-latency data transmission and ease of deployment within standard residential infrastructure.
The wearable unit utilizes the Raspberry Pi Zero 2 W's integrated IEEE 802.11 b/g/n (Wi-Fi) interface to establish a secure connection to the local Wireless LAN (WLAN). Data packets containing physiological metrics (ECG waveforms, heart rate variability, skin conductance) are serialized and transmitted directly to the Google Firebase Realtime Database via a secure REST API or WebSocket connection. This topology minimizes the hardware footprint by eliminating the need for intermediate gateways, relying on standard home internet infrastructure to ensure cost-effectiveness for mass adoption.

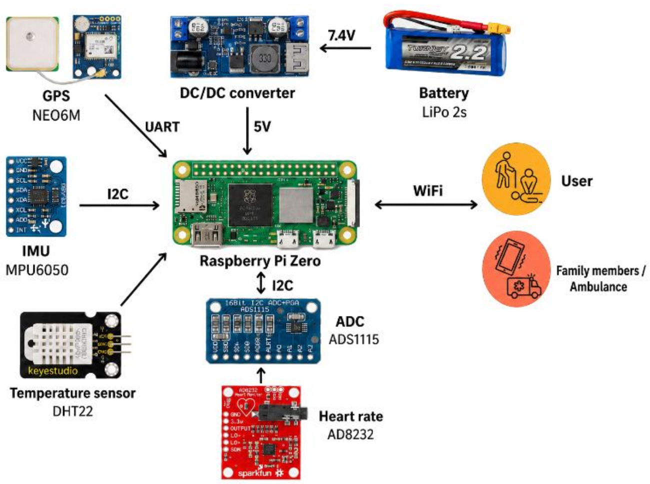

Figure 4: Healthcare Application System Diagram.

B. Military System Topology (LoRaWAN-Based)

The military configuration addresses the "denied environment" constraint, where cellular or Wi-Fi infrastructure is non-existent, unreliable, or compromised. In this mode, the system bypasses the onboard Wi-Fi in favor of the RFM9x LoRa (Long Range) Transceiver. The architecture introduces a local LoRa Gateway (implemented using a Raspberry Pi 5). The wearable nodes function as end-devices, broadcasting compressed telemetry packets over the 915 MHz ISM band using the LoRaWAN protocol [14]. This modulation technique, based on Chirp Spread Spectrum (CSS) [15], enables robust communication over distances exceeding several km in line-of-sight conditions [16], offering high immunity to interference. The local Gateway acts as a packet forwarder and edge-aggregator; it can collect data from multiple soldiers' units and uplinks it to the central command dashboard via satellite or secured long-haul backhaul when available. Future work will explore adaptive strategies to optimize LoRaWAN performance under varying channel and load conditions [17].

C. Sensing layer

The system integrates five key sensors to capture a comprehensive physiological and contextual profile [2]:

- ECG (AD8232): Measures the electrical activity of the heart.
- GSR (Grove Sensor): Measures skin conductivity, a proxy for sympathetic nervous system activity and stress levels.
- IMU (MPU6050): A 6-axis accelerometer and gyroscope for activity classification, fall detection, and posture analysis.
- Temperature (DHT22): Monitors ambient and close-to-body temperature/humidity for thermal stress assessment.
- GPS (NEO-6M): Provides real-time geolocation for contextual data tagging and tracking.
- The Analog-to-Digital Conversion (ADC) is handled by an external ADS1115 16-bit module, necessary because the Raspberry Pi Zero 2W lacks built-in analog inputs. The ADS1115 interfaces with the Pi via the I2C bus.

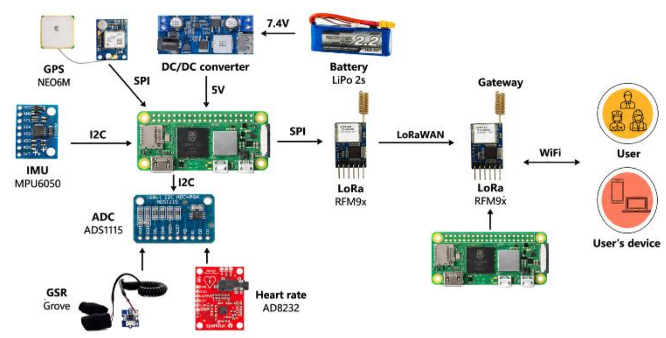

Figure 5: Military Application System diagram

D. Standard Communication Protocols

To ensure interoperability and signal integrity across the internal hardware stack, VitalMesh enforces strict adherence to standard industrial protocols:

- Inter-Integrated Circuit (I2C): Employed for short-distance, on-board communication with the ADS1115 Analog-to-Digital Converter and the MPU6050 IMU. This multi-master bus minimizes GPIO usage while maintaining sufficient bandwidth (up to 400 kbit/s) for sampling physiological signals.

- Serial Peripheral Interface (SPI): Utilized for high-throughput communication with the LoRa transceiver, ensuring that radio transmission latency does not bottleneck the sensor acquisition loop.

- UART (Universal Asynchronous Receiver-Transmitter): Dedicated to the NEO-6M GPS module for parsing NMEA sentences continuously.

- OAuth 2.0: Implemented at the application layer to manage secure, token-based authentication, ensuring that sensitive health data remains accessible only to the data owner and authorized medical personnel.

E. Power System

The wearable node is powered by a 7.4 V (2S) Li-Po battery. A DC/DC buck converter regulates the supply to a stable 5 V rail used by the Raspberry Pi and the sensor modules. Based on the converter datasheet, the 5 V conversion efficiency is approximately ~ (0.75–0.80). With this power architecture, the prototype targets a continuous operating time on the order of 4–6 hours using a 1000 mAh battery, and the runtime scales approximately linearly with capacity (e.g., a 2000 mAh pack provides roughly 2× longer operation).

F. Battery Life

Battery life was estimated using worst-case current consumption. The Raspberry Pi Zero 2 W draws approximately 120 mA during continuous operation. The sensor suite contributes on the order of ~100 mA in total, with the GPS module being the largest contributor (typically ~50 mA) and the remaining sensors/ADC accounting for the rest. This yields an overall 5 V load current of roughly ~0.27–0.30 A. Accounting for the DC/DC conversion efficiency (0.75–0.80), the corresponding battery-side current is approximately ~0.24 A, which results in an estimated runtime of about ~4 hours for a 1000 mAh (1 Ah) battery. In practice, runtime can be 1–2 hours longer depending on workload, sampling rates, and wireless activity. Battery life can be extended by reducing GPS duty cycle, lowering sampling rates when high-resolution data is not required, and applying duty-cycling to sensors and communications based on the deployment scenario.

IV. IMPLEMENTATION

The implementation phase focused on three key areas: hardware integration, embedded software development, and the user application.

A. Hardware Integration

The Raspberry Pi Zero 2W manages sensors with their different communication protocols (see Fig. 4):

- I2C: Used for the MPU6050 (IMU) and the ADS1115 (ADC, which reads ECG and GSR).
- SPI: Used to interface with the LoRa RFM9x transceiver module for long-range communication.
- Serial: To communicate with the GPS, to receive the coordinates.

B. Embedded Software

The Raspberry Pi runs a lightweight Linux distribution (Raspberry Pi OS Lite) with custom Python modules. The software is organized into three main layers:

- Acquisition Layer: Reads raw sensor data at predefined sampling rates.
- Preprocessing Layer: Performs filtering, normalization, and packaging.
- Communication Layer: Handles Wi-Fi or LoRaWAN transmission based on operational mode.

The code running on the Raspberry Pi is written in Python. Key software functionalities include:

- Sensor Polling: Real-time collection and sampling of data from all sensors.
- Signal Pre-processing: Basic filtering and scaling of raw sensor data.

V. IMPLEMENTATION

To ensure a reproducible and isolated software environment, the embedded codebase was developed within a dedicated Python *virtual environment* (venv). This approach prevented dependency conflicts with the Raspberry Pi's system-wide packages and allowed precise version control of all required libraries, including sensor drivers, asynchronous I/O modules, and Firebase communication packages.

Data Structuring: Formatting the collected data into JSON objects, tagged with a unique device ID and a precise timestamp.

Communication Management: Sending the JSON payloads to the Firebase backend.

A. Application and Cloud Infrastructure

Cloud Backend (Firebase): Used as the primary data repository and authentication service. Firebase Realtime Database is leveraged for its low-latency data synchronization, crucial for real-time monitoring. User and device authentication is implemented using Firebase Auth (OAuth 2.0). For credential protection, user passwords are stored using the scrypt password-hashing function, a memory-hard KDF designed to increase resistance against brute-force and GPU/ASIC attacks [18].

The data received by the database comes from each sensor with a timestamp and unique ID to identify each user. It also provides a historical log of all the previous data, with the timestamp and user id, so we can keep track of the past performances of the users in one unique place, completely securely. The database rules define who has access to it and under what conditions (what data they can read or write). For this first prototype the database is completely open but it still defines what type of data is authorized for each sensor (string, int, multiple types) which allows the database already to filter the data received from the database.

Mobile Application (Android): Developed in Kotlin using the modern Jetpack Compose framework. The application provides two main functionalities: secure user login/authentication and a real-time dashboard for visualizing health metrics (Heart Rate, Stress Level, Body Temperature, Location, and Activity Status) retrieved from Firebase. In the Figure 6 we can see the different views of the App interface. Starting from the top left, we have the login screen, then the main dashboard on the top right; at the bottom left we see a view of the geolocation in google maps; finally, at the bottom right we can see the detailed view of one of the sensor measurements (concretely, the GSR sensor readings).

B. Communication over LoRa

To address deployment scenarios lacking reliable internet infrastructure, such as military fields or remote areas, we established a long-range communication link utilizing RFM9x LoRa modules. This architecture employs a "Gateway" topology, where the primary wearable node (Raspberry Pi Zero 2 W) acts as the transmitter, and a secondary unit (Raspberry Pi 5) functions as the receiving Gateway.

This configuration bridges the connectivity gap by transmitting sensor telemetry via the 915 MHz LoRa band to the Gateway, which subsequently uploads the data to the Firebase Realtime Database via a local Wi-Fi connection. This dual-hop mechanism ensures that the system maintains full functionality and data synchronization with the mobile application even when the user is outside standard Wi-Fi range. Field validation confirmed reliable data transmission from the sensor array to the application over a line-of-sight range of approximately 1 km. Figure 5 illustrates this implementation, depicting the transmitter node (left) and the Gateway receiver (right).

VI. RESULTS

The development of VitalMesh resulted in a fully functional prototype that successfully demonstrated simultaneous multi-sensor data acquisition and robust wireless transmission in both Wi-Fi and LoRa scenarios. See in Figure 3 the final prototype of Vital Mesh.

During implementation, each part of the system was built and tested step by step to ensure everything worked correctly before combining the components. Sensors, communication modules, and software features were first validated individually, which made it easier to identify issues early. Once each module was stable, they were integrated into the full system and tested again to confirm consistent data flow from acquisition to cloud storage. This progressive approach helped maintain reliability throughout development and ensured that the final prototype functioned as expected. Sections A–D below present an overview of the system functionality, a comparative analysis with existing solutions, the current limitations of the prototype, and the privacy and ethical considerations guiding the design of VitalMesh.

A. System Functionality

All five sensors were successfully interfaced with the Raspberry Pi Zero 2W using the required protocols (I2C, SPI) via the external ADS1115 ADC necessary to convert the analog signal of the heart rate sensor, and potential future sensors that require an analog to digital conversion.

Data packets for all metrics were successfully transmitted, authenticated, and stored in the Firebase Realtime Database with an imperceptible data latency in the Wi-Fi scenario.

The LoRa module successfully established communication with the designated Gateway, validating the system's viability for the Military deployment scenario. The range test confirmed effective data transmission up to approximately 1 km in line-of-sight conditions, using a simple quarter-wave antenna.

B. Comparative Analysis

Compared to existing smart apparel, VitalMesh offers a highly competitive feature set. While commercial solutions often require expensive subscription models or focus on limited metrics, VitalMesh provides a multi-metric, context-aware solution in a comfortable, open-source-driven platform, making it a highly cost-effective and versatile choice for researchers and specialized applications.

C. Limitations

While the VitalMesh prototype successfully demonstrates the proof-of-concept, several limitations regarding hardware scalability, sensor fidelity, and software optimization were identified during the validation phase. The current architecture relies on the Raspberry Pi Zero 2 W, which, while compact, presents constraints regarding its General Purpose Input/Output (GPIO) interface. The limited number of available pins restricts the "modular" quality of the device, creating a bottleneck for adding future sensors without complex multiplexing. Furthermore, the shared I2C bus topology required extensive manual cabling to interface multiple sensors. This reliance on manual interconnects introduces mechanical vulnerabilities, making the circuit susceptible to signal artifacts caused by the natural movement of the wearer [19].

These cabling constraints also impact the physical practicality of the garment. To minimize signal degradation over long wires, sensors were forced into a clustered configuration near the central processing unit. This concentrated placement negatively affects the weight distribution of the vest, potentially causing user discomfort during prolonged use.

Also, a word can be said about the reliability of the sensors, the heart rate sensor needed an important processing before being useful and read correctly, the GPS also performed poorly indoors and required tests outside to find a “fix” and get reliable data. The GSR sensor, even though it worked needed to be converted from a conductivity level to a stress level, which can be questioned given the high subjectivity of this data (especially when rated out of 100). To use all those sensors correctly we believe that with more tests, on different people we could come up with a code that adapts the value to each individual by taking measures of the users in different state to calibrate the devices in function of each user.

Lastly, the architecture of the code could be greatly improved, especially on the embedded part, regarding the problematics of speed and optimization that have been overlooked. An improvement of our system could be different drivers for each sensor that communicates with a central script that would send the data to our database.

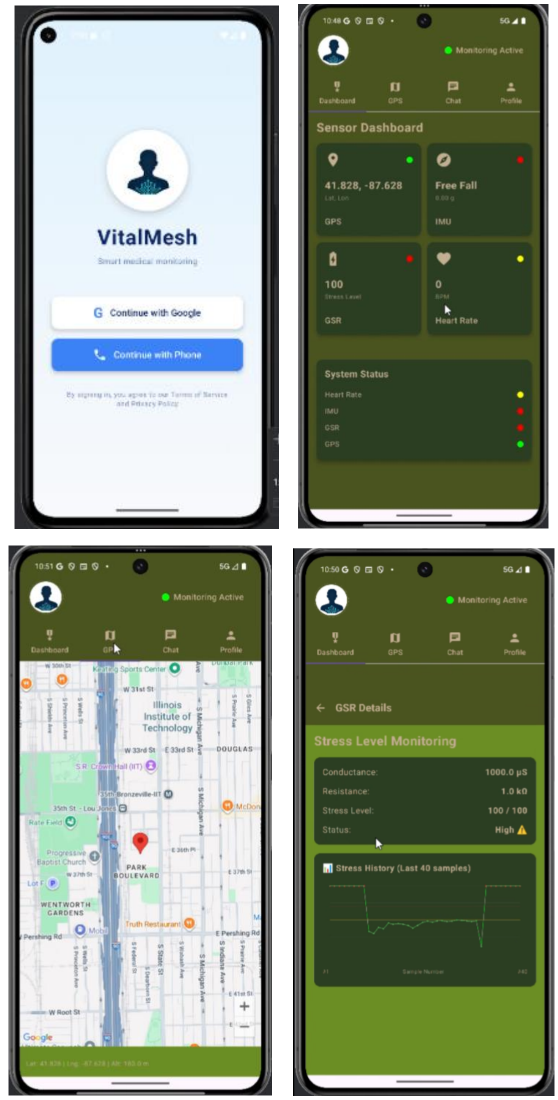

Figure 6: different views of the App interface.

In conclusion, all these flaws come from the prototype nature of the presented solution. With better resources and more time for developing and testing, all these limitations could be patched.

D. Privacy and Ethical Considerations

Given the sensitivity of physiological data, VitalMesh incorporates not only technical safeguards but also a framework for ethical data handling. The system is designed to minimize data retention, transmitting only essential features while allowing users to delete or restrict access to their historical records. Role-based access control ensures that clinicians, researchers, and end-users have clearly delineated permissions, reducing the risk of data misuse. Additionally, all geolocation data is anonymized during long-range transmission modes to protect military personnel and high-risk users from potential tracking. These considerations align the platform with emerging digital health standards and strengthen its suitability for real-world deployment [20].

VII. CONCLUSION

The VitalMesh project has successfully completed its proof-of-concept phase, demonstrating a robust multi-sensor smart textile platform for continuous physiological monitoring. The system met key design goals, including dual-channel communication (Wi-Fi and LoRaWAN), a modular and durable hardware architecture addressing washability challenges, and secure integration with a cloud backend and user-friendly mobile application. These results confirm the platform's readiness for further development and clinical testing.

VitalMesh is a platform suitable for expansion, with clear pathways for optimization and feature growth. Power efficiency will be improved through a custom power management PCB and lower-consumption, smaller sensors, targeting 24-hour battery life [21]. Additional testing and sensor calibration workflows will enable user-specific tailoring, requiring further software, database, and app development. Advanced analytics will integrate on-device machine learning for real-time anomaly detection and reduced data transmission. Textile engineering efforts will explore specialized conductive materials to improve signal quality and durability. Finally, expanded sensing capabilities, including SpO_2, gas, smoke, and radiation detection, will enhance medical and military applications.

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