VitalWave: An End-to-End Open-Source High-Frequency Wearable Device and Data Collection Platform

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***Abstract*—We present an initial prototype for *VitalWave*, a novel open-source end-to-end platform consisting of a wearable device and corresponding mobile/web application capable of capturing and visualizing high-frequency sensor data. The platform includes cloud-based data processing and a web interface for data visualization and analysis. This system was designed to overcome the limitations of existing commercial wearables, which often only offer low-frequency, pre-processed data and limited raw data access. Our device samples at up to 100Hz from multiple biosensors and includes real-time mobile streaming, secure cloud storage, and integrated web-based visualization tools. Ultimately, this work serves as a foundational platform for the development of digital biomarkers and machine learning models in health applications.**

***Index Terms*—digital biomarkers, wearable device, mobile app, high-frequency sensors, cloud platform**

I. Introduction

Digital biomarkers—objective, quantifiable physiological and behavioral data collected through digital devices—are transforming health monitoring by enabling continuous, passive, and real-time assessment of human health in free-living environments [1]. Advances in wearable technologies have opened new opportunities for early detection and personalized management of a range of conditions, including cardiovascular disease, neurological disorders, respiratory illnesses, and mental health challenges [2], [3]. These digital signals, such as changes in heart rate (HR), heart rate variability (HRV), skin temperature, sleep patterns, and activity levels, have been shown to correlate with clinical outcomes and disease trajectories [4].

Despite this promise, current commercial wearables typically provide low-resolution data that is pre-processed on-device and sampled at relatively infrequent intervals. Furthermore, proprietary APIs often limit access to raw signals or introduce latency between data capture and data availability, restricting their usefulness for real-time event detection or algorithm development. While consumer devices like the Apple Watch, Fitbit, and Garmin are valuable for long-term health tracking, their design prioritizes battery life and user-facing features over research-grade data fidelity and transparency.

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A. Existing Research-Grade Wearable Platforms

Several research-grade devices, such as the Empatica Embrace and Shimmer3 offer access to high-frequency physiological signals but are limited by high cost, closed-source ecosystems, and hardware constraints. The Embrace supports seizure monitoring with FDA clearance but lacks extensibility and requires a subscription for data access. Shimmer3 provides modular sensing and high sample rates, yet its bulk, reliance on proprietary software, and short battery life reduce its suitability for continuous, wearable deployment [5], [6].

While these devices have accelerated digital biomarker discovery and enable straightforward, out-of-the-box implementation, several open-source platforms have been developed to reduce cost and data-access barriers:

- **Wearable Monitoring Platform (WMP).** Baldini *et al.* introduced a fully open-source IoT architecture that fuses multiple off-the-shelf sensors via a Python "Sensor Fusion Unit", streams data over Message Queuing Telemetry Transport, and processes features in real time with InfluxDB and CouchDB back-ends. However, this approach does not integrate the sensors into a single cohesive wearable device, limiting its practicality for continuous, real-world physiological monitoring [7].
- **OpenHealth.** Bhat *et al.* proposed a reference hardware/software stack with flexible-hybrid electronics for autonomous activity and tremor monitoring. The design emphasizes standardized sensor connectors, ultra-low-power MCU operation, and open HDL files for reproducibility [8].
- **Lumos Spectroscopy Device.** Watson *et al.* presented Lumos, an Arduino-based wearable that captures visible + NIR spectra for on-body tissue optics research (e.g., non-invasive glucose, hematoma detection). All PCB files, firmware, and calibration tools are openly released [9].
- **RADAR-Base.** Ranjan *et al.* built an end-to-end mHealth platform around Apache Kafka that ingests smartphone and wearable streams (Empatica E4, Fitbit, etc.) and was scaled to study thousands of participants in neurological and psychiatric cohorts [10].

B. VitalWave System

While many solutions exist to date, none combine all of the following desirable features into one solution, we introduce *VitalWave*, an open-source, extensible hardware and software platform designed for high-resolution physiological data collection, real-time analysis, and digital biomarker development. *VitalWave* enables cost-efficient, multimodal sensing with flexible configurations and a fully integrated software stack—including a mobile application for real-time streaming and secure data transfer, a cloud-based pipeline for automated data processing, and a web dashboard for visualization, user management, and closed-loop control.

The full open-source hardware and software resources are publicly available at [11], and include the following contributions:

- A low-cost, high-frequency, multi-sensor wearable hardware platform.
- A 3D-printed wearable case.
- An iOS mobile app for real-time data acquisition and secure transmission.
- A cloud infrastructure for automated extraction and processing of digital biomarkers.
- A web interface for visualization, analysis, and remote system management.

II. System Components

The system (Fig. 1) includes a wearable device, iOS app for data collection, cloud platform, and web app for viewing data. This section provides a detailed overview of each component and their interactions.

A. Wearable Device

The wearable device includes a custom printed circuit board (PCB) design and is equipped with a 9-axis accelerometer, thermistor, gyroscope, photoplethysmography (PPG) sensors, and magnetometer sampling up to 100Hz. The device architecture is built around the Nordic nrf5240 System on Chip (SoC) (Table I).

The device supports a minimum 3-day battery life under standard usage, including active data streaming. Power-saving features allow for scheduled sensor activation and Bluetooth Low Energy (BLE) communication. Long-term flash storage on-device enables data capture even in the absence of an active Bluetooth connection, with asynchronous uploading enabled once reconnected.

The firmware includes BLE communication protocols for efficient data transmission and supports Over the Air (OTA) firmware updates. Sensor data is streamed using Generic ATTribute (GATT) profiles, with custom characteristics for each signal type. The wearable casing is water-resistant, ergonomically designed, and similar in size to existing commercial wearable devices (Fig. 2).

B. Mobile App with Real-Time Raw Data Monitoring

The iOS mobile app allows users to pair and collect data from nearby devices. Multiple devices can be paired at once allowing for multi-nodal data collection (i.e., simultaneous data collection at different body locations or from multiple users). Using the app, users can name and manage the paired devices individually. All collected raw sensor data is synced to the application and uploaded to Firebase Storage under anonymized user and device ids as CSV files. Raw data CSV files can be viewed directly from the app and users can disable cloud syncing to accommodate stringent human research privacy requirements that may exist in certain environments.

Users can also flag timestamps with the push of a button on the device such that events can be marked in the data, which is useful for downstream data analysis and harmonization. Timestamped metadata—such as activity labels or external events—can be appended to each session using the iOS app, either by browsing existing timestamps created by the device's

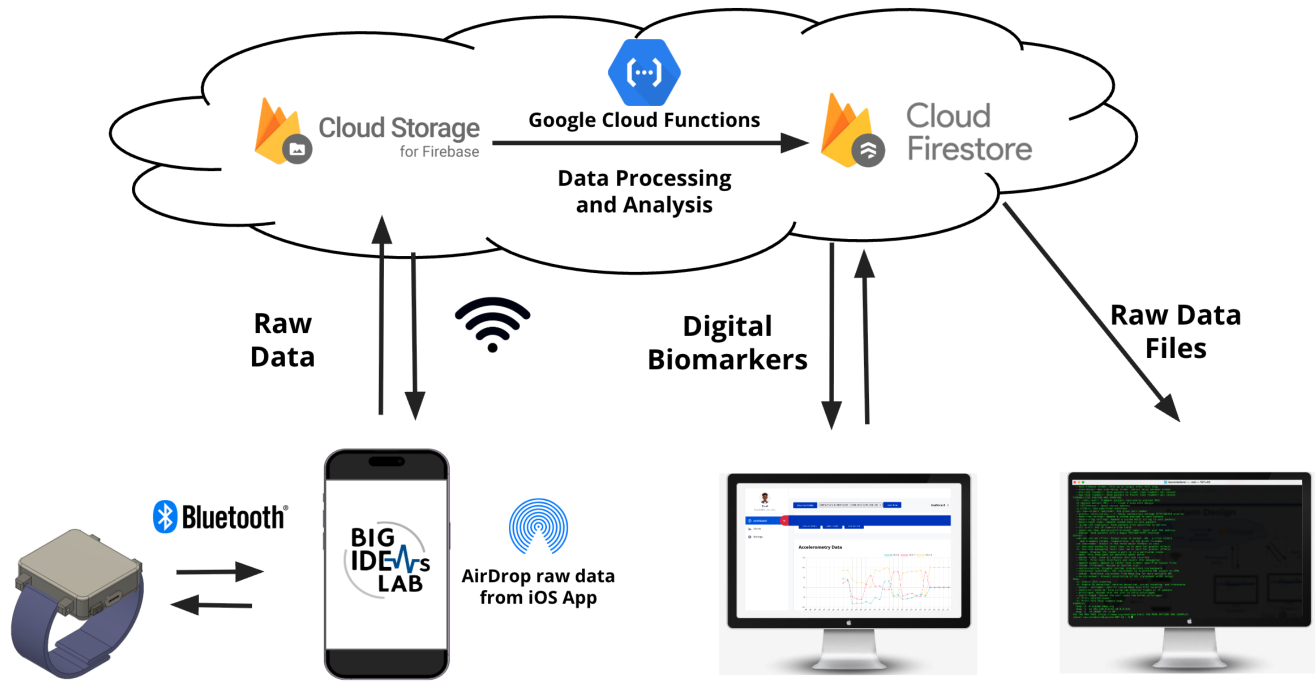

Fig. 1. Overview of the full *VitalWave* system including sensors, data flow, and user interfaces.

TABLE I
CORE ELECTRONIC COMPONENTS INTEGRATED INTO THE *VitalWave* PROTOTYPE

Function	Part No.	Measured / Supported Signals	Configured Fs
System-on-Chip (MCU + BLE)	nRF5240	64-MHz Arm Cortex-M4F, 2.4 GHz BLE/ANT/Thread	—
IMU + Temperature	LSM6DS3TRC	3-axis ACC, 3-axis GYR, die temp	100 Hz
Optical PPG	MAX86916	HR / SpO_2 (Green, Blue, Red, and IR LEDs)	100 Hz
Magnetometer	LIS3MDL	3-axis magnetic field	25 Hz
Humidity (RH + Temp)	SHT31	Relative humidity, ambient temp	1 Hz

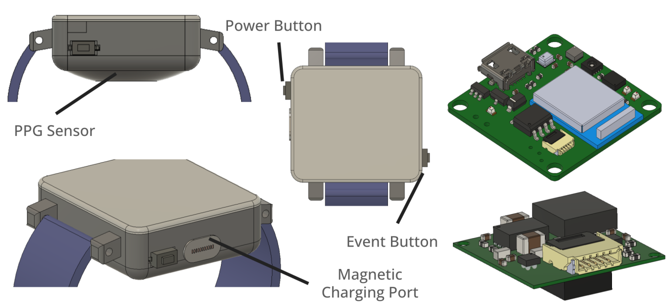

Fig. 2. Wearable Device

button or by manually creating new ones. Additionally, the iOS App offers real-time live raw data monitoring as data is streamed over BLE.

C. Cloud-Based Data Processing

Google Cloud Functions can be triggered at fixed intervals or upon data upload to process the sensor data and generate digital biomarkers. The raw sensor data is processed through a series of pipelines that extract physiological metrics used to inform downstream machine learning models. The pipeline incorporates both in-house processing tools and third-party libraries. NeuroKit2, an open-source Python package for neurophysiological signal processing, is employed to extract detailed cardiovascular features from PPG and accelerometry data [13]. The integration with NeuroKit2 allows for reproducible extraction of cardiovascular features, aligning the digital biomarkers with commonly accepted standards. These features are computed on a per-minute basis and stored in a structured format for downstream visualization and modeling. The pipeline includes step and movement detection derived from accelerometer and gyroscope data processed using Fusion, an IMU sensor fusion library [12]. One-minute summaries of each biomarker are computed and stored in Firestore, a NoSQL document database for efficient rendering in the web dashboard. The architecture enables scalable, real-time signal transformation and feature generation, forming the foundation for subsequent algorithm deployment that is suitable for just-in-time, adaptive interventions including clinical applications.

D. Web App and Data Visualization

The web app allows users to make an account and view the data collected by their respective wearable devices. The web app includes plots of HR, HRV, and steps. All raw sensor data is stored on GCS and is accessible through Firebase Cloud Storage for downstream data analysis.

III. Initial Testing

Initial testing of the VitalWave system focused on evaluating sensor performance, signal quality, and end-to-end data pipeline functionality—including mobile, cloud, and web infrastructure.

Sensor Validation. A series of 10-minute walking trials were conducted to assess the performance of the PPG, accelerometer, and gyroscope sensors. Data were successfully streamed via BLE to the iOS application with no packet loss reported in the logs. Heart rate estimates derived from the PPG signal were compared against a commercial reference device (Polar H10), confirming physiological relevance.

Signal Quality. Time- and frequency-domain analyses revealed clean, periodic waveforms in both heart rate and motion signals. The accelerometer and gyroscope signals captured gait cycles clearly during walking, with identifiable stride periodicity and low drift.

Cloud and Web Infrastructure. End-to-end testing of the data pipeline confirmed reliable data transmission from the iOS app to the cloud server via secure HTTPS. The automated cloud pipeline processed incoming data to extract summary statistics (e.g., average HR, step counts) with correct alignment of timestamps. The web dashboard successfully displayed data visualizations for incoming wearable data.

IV. Conclusion

In this work, we introduced *VitalWave*, a fully open-source end-to-end hardware and software platform for high-frequency physiological data capture, streaming, processing, and visualization. Designed to improve upon existing commercial and research-oriented wearables, *VitalWave* provides researchers with full access to raw sensor streams—including PPG, IMU, magnetometer, and environmental data—at user-defined sampling rates of up to 100 Hz. Its modular architecture, spanning a custom wearable device, iOS app, cloud backend, and web dashboard, enables real-time monitoring, offline logging, and retrospective analysis across diverse research settings.

Initial testing demonstrated that *VitalWave* reliably captures high-quality multimodal data during ambulatory activity, with stable BLE connectivity, battery life exceeding 3 days, and successful integration with third-party processing libraries such as NeuroKit2. These results support its feasibility for short- to medium-term free-living deployments and lay the groundwork for broader applications in digital biomarker development.

***VitalWave*'s future evolution** will focus on three main directions:

1) **Clinical Validation and Sensor Expansion:** We will formally validate HR and HRV metrics against ECG and compare SpO_2 estimates to FDA-cleared pulse oximeters during activities of daily living. Additional sensors (e.g., electrodermal activity, skin temperature) and Android support are planned to extend the system's versatility.
2) **Intelligent Sensing and Edge Processing:** Firmware updates will introduce adaptive sampling strategiesy, optimizing both battery life and data resolution. We also plan to support preliminary on-device biomarker computation for scenarios with intermittent connectivity.
3) **Software Integration and Cloud Intelligence:** *VitalWave* will be interoperable with the *Digital Biomarker Discovery Pipeline* (DBDP) [14], enabling seamless ingestion into standardized preprocessing and machine learning workflows. Cloud platform enhancements will include real-time anomaly detection and longitudinal data.

With its open architecture, raw data access, and extensible analytics stack, *VitalWave* directly complements the goals of open frameworks like the DBDP and has the potential to accelerate reproducible, community-driven digital biomarker discovery across domains such as infection detection, mental health, cardiovascular monitoring, and chronic disease management.

References

[1] S. R. Steinhubl, E. D. Muse, and E. J. Topol, "The emerging field of mobile health," *Sci. Transl. Med.*, vol. 7, no. 283, pp. 283rv3, Apr. 2015.

[2] J. Torous, R. Onnela, and M. Keshavan, "New dimensions and new tools to realize the potential of RDoC: digital phenotyping via smartphones and connected devices," *Transl. Psychiatry*, vol. 7, no. 3, pp. e1053–e1053, 2017.

[3] B. Caulfield et al., "Digital health interventions for the prevention of cardiovascular disease: A systematic review and meta-analysis," *Eur. J. Preventive Cardiology*, vol. 26, no. 5, pp. 498–506, 2019.

[4] N. S. J. Jacobsen and A. Mamen, "Wearables and digital biomarkers in lifestyle-related diseases: A scoping review," *Digital Health*, vol. 9, pp. 1–12, 2023.

[5] Empatica, "Empatica EmbracePlus" Empatica Inc. [Online]. Available: https://www.empatica.com/embraceplus.

[6] Shimmer Sensing, "Shimmer3 GSR+ Unit Specifications," [Online]. Available: https://www.shimmersensing.com/products/gsr-sensor/.

[7] G. Baldini et al., "A wearable platform to support affective computing applications," *Electronics*, vol. 12, no. 6, p. 1498, Mar. 2023.

[8] A. Bhat et al., "OpenHealth: Towards low-cost, standardized, wearable health monitoring," *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.*, vol. 6, no. 1, pp. 1–24, 2022.

[9] B. Watson et al., "Lumos: A spectroscopy device for wearable tissue optics," *IEEE Sens. Lett.*, vol. 3, no. 3, pp. 1–4, Mar. 2019.

[10] Y. Ranjan et al., "RADAR-base: An open-source platform for mobile health in mental health and neuroscience research," *JMIR mHealth uHealth*, vol. 7, no. 8, p. e11734, Aug. 2019.

[11] L. Lederer, "VitalWave," https://github.com/Big-Ideas-Lab/VitalWave.

[12] xioTechnologies, "Fusion," https://github.com/xioTechnologies/Fusion.

[13] D. Makowski, T. Pham, D. Lau, *et al.*, "NeuroKit2: A Python toolbox for neurophysiological signal processing," *Behav. Res. Methods*, vol. 53, pp. 1689–1696, 2021, doi: 10.3758/s13428-020-01516-y.

[14] B. Bent, K. Wang, E. Grzesiak, *et al.*, "The digital biomarker discovery pipeline: An open-source software platform for the development of digital biomarkers using mHealth and wearables data," *J. Clin. Transl. Sci.*, vol. 5, art. e19, pp. 1–8, 2021, doi: 10.1017/cts.2020.511.