

Smart Ear Probe for Vital Monitoring

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Abstract—Continuous vital parameter monitoring is becoming increasingly important in telemedicine, early diagnosis, and personal health management. Though the traditional methods of monitoring, such as fingertip pulse oximeters, chest belts, and digital thermometers, are very accurate, they are not suitable for continuous or long-term use because of their bulkiness and discomfort. This paper demonstrates a compact, ear-mounted wearable device that is able to monitor heart rate, SpO₂, respiration rate, and body temperature by combining PPG sensing, in-ear acoustic detection, and digital temperature measurement. This device uses Bluetooth Low Energy (BLE) for wireless communication with a dedicated mobile application to enable real-time visualization, data storage, health tracking, and user notifications.

The ear was chosen as the location for sensing due to its stable blood perfusion, low motion interference, proximity to core temperature, and natural ergonomic anchoring, supported by previous literature. A custom PCB integrates a MAX30102 PPG module, MEMS microphone, temperature sensor, ESP32 microcontroller, battery, and charging module. The app provides a user dashboard, graphical trends, alarm system and enables seamless device pairing.

This work demonstrates the feasibility of a compact, user-friendly wearable ear-based monitoring system with integrated hardware and mobile software for continuous health management.

Index Terms—Wearable sensors, ear-PPG, mobile health app, BLE communication, respiration sensing, temperature monitoring.

I. INTRODUCTION

The monitoring of vital signs is central to the assessment of physiological status, allowing for early diagnosis and continuous monitoring of health. Considering the current emphasis on preventive medicine, remote monitoring, and personalized medicine, there is an emerging need for devices that can offer continuous acquisition of accurate

physiological information without causing discomfort or interfering with daily activities. While clinically reliable data are provided by traditional medical instruments such as fingertip pulse oximeters, digital thermometers, and chest belts, they are intrinsically not suited for long-term use due to their bulkiness, being stationary, and requiring specific body positions. This has naturally driven the development toward wrist-worn wearables, which, however, continue to face challenges like motion artifacts, inconsistent skin perfusion, low signal quality during motion, and poor sensor-to-skin surface alignment.

Because of several inherent advantages, the human ear has been considered a very promising anatomical site for physiological monitoring. The vascular structure around the concha and tragus provides rich blood perfusion that can remain stable during moderate physical movement, thereby enabling much cleaner and more reliable PPG waveforms. The skin and muscle tissue at the location also have minimal displacement during daily activities, thus offering a significantly lower susceptibility to motion artifacts than does a wrist or fingertip. Its proximity to the body's core allows it to provide more reliable temperature assessment, with the thermal environment of the ear canal being pretty well insulated from ambient influences. Most importantly, due to being a naturally comfortable anchoring point akin to common consumer devices like earphones or hearing aids, it presents an ideal site for continuous monitoring applications. These factors drive the development of a compact, ear-mounted device that can measure multiple vital signs simultaneously. This work has been conducted in such a way that optical PPG sensing, acoustic respiration detection, and digital temperature monitoring are integrated into one wearable module, along with a smartphone application that displays physiological data in real time. Thus, this hardware-software integrated combination provides a complete

ecosystem for monitoring that can be carried on continuously, unobtrusively, and conveniently in daily life. The goal of this work is to propose not just a hardware design but an intelligent workflow for acquisition, processing, transmission, and visualization and, thus, to demonstrate the feasibility of ear-based multi-vital sign monitoring for practical healthcare.

II. RELATED WORKS

Wearable physiological monitoring has undergone significant evolution over the last ten years, with a multitude of commercial and academic efforts aimed at developing compact devices capable of delivering reliable health insights. The majority of commercial devices depend on wrist-based photoplethysmography, largely because it is convenient to wear and socially acceptable. However, considerable studies have demonstrated that wrist-based PPG is subject to significant inaccuracies due to physical movement, variations in ambient conditions, low perfusion states, and incorrect device placement. The optical path at the wrist is often interrupted by tendons, shifting of the underlying muscles, and thickness of the skin, all contributing to making the wrist a poor location for consistent physiological monitoring.

These factors have motivated academic research into alternative anatomical sites in an attempt to improve accuracy and comfort. Several previous studies have already been conducted showing that the ear gives a more stable PPG waveform compared with that from the wrist and the fingertip. This is because the ear is relatively isolated from major muscle groups; hence, the optical signal is less corrupted by movement. Other researchers have also looked into utilizing in-ear microphones and accelerometers to capture thoracic and airway-related acoustic signatures, which can expose respiration rate and breathing patterns. These acoustic signals are particularly useful because the ear canal acts as a natural resonator that enhances low-frequency respiratory sounds.

The requirement for wearables to be coupled to smartphone applications has further been evidenced through the growth of mobile-health and telemedicine platforms. Progressive healthcare systems encourage continuous monitoring, access to historical trends, and intuitive data visualization. As such, most wearable medical devices are expected to interface naturally

with a companion software system. To date, few devices integrate multiple sensing modalities—namely, PPG, respiration acoustics, and temperature measurement—into one ear-mounted form factor while enabling real-time data visualization using a dedicated mobile application.

This work addresses this gap by integrating hardware miniaturization, multi-sensor integration, Bluetooth Low Energy communication, and a fully functional mobile dashboard into one cohesive system, specifically designed around the advantages of the ear as a sensing location.

III. METHODOLOGY

A. Sensor Data Acquisition

The operation of the proposed ear-mounted multi-vital monitoring system starts with the acquisition of raw physiological signals through integrated sensors. The PPG sensor (MAX30102) works by shining red and infrared light into the vascular region of the ear and then detecting the amount of light reflected back to the photodiode. These reflections vary in response to the pulsatile changes in blood volume arising from cardiac cycles and thus generate a waveform from which heart rate and oxygen saturation can be obtained. The MEMS microphone positioned at the entrance of the ear canal picks up respiration-related sounds produced due to airflow turbulence and slight internal vibrations. These acoustic fluctuations show rhythmic patterns corresponding to the phases of inhalation and exhalation, allowing an estimation of the respiration rate. Complementary to these sensors, the digital temperature sensor measures ear surface temperature continuously. Unlike the external skin areas, which are significantly influenced by ambient conditions, the ear offers a more thermally stable location, whose readings approximate core temperature trends quite well. Therefore, all of these sensors together provide continuous raw signal capture representative of the user's physiological state.

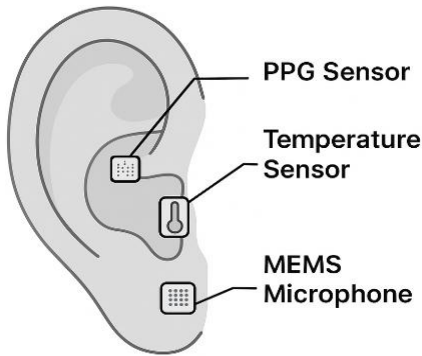


Fig. 1 Sensor placements on the ear

B. Raw Signal Pre-processing

The raw signals, after acquisition, are routed to the ESP32 microcontroller for some preprocessing prior to further analyses. The PPG signal usually contains a number of noise components, including high-frequency electronic noise, low-frequency baseline drift, and disturbances resulting from sudden movements or changes in sensor pressure. This is handled by the microcontroller through digital filtering that separates the physiologically meaningful portions of the waveform. It eliminates baseline wander through high-pass filtering and unwanted high-frequency components by low-pass filtering. The microphone signal undergoes filtration to remove background noise and emphasize respiratory acoustic components. This stage is obviously done to clean up and stabilize the signals appropriately to reduce the likelihood of false detections or incorrect measurements in further steps of feature extraction.

C. PPG Signal Processing

Meaningful physiological parameters are extracted from the filtered PPG waveform. The periodic peaks within the waveform correspond to systolic blood volume expansion, from which heart rate can be derived. Peak detection algorithms detect these maxima and calculate the time intervals between consecutive peaks to derive beats per minute. SpO_2 is calculated by determining the ratio of the AC component to the DC component of red and infrared light absorption, using a priori knowledge of the relationship between absorption ratio and oxygenation level. Further processing of the signal examines motion-induced distortions, and adaptive algorithms may be used to help discriminate between genuine physiological pulses and noise artifacts. Some of the

basic vital signs extracted from the optical subsystem of the device during this stage are:

D. Acoustic Respiration Processing

The extraction of the respiration rate is based on the analysis of acoustic patterns captured by the MEMS microphone. Respiratory sounds fall within a specific frequency range; therefore, the filtered audio signal is analysed in order to isolate these characteristics. The system applies band-pass filtering to emphasize the frequencies associated with breathing. When the relevant band is isolated, an envelope detection method will convert the acoustic waveform into a smoother signal, underlining the cyclical pattern of breathing. Its rising and falling segments correspond to inhalation and exhalation phases, respectively. The analysis of zero crossings, peak intervals, or amplitude fluctuations within this envelope will help in estimating the exact rate of respiration. This approach enables non-contact, comfortable respiratory monitoring without requiring chest movement sensors or nasal cannulas.

E. Temperature Signal Processing

The continuous temperature sensor outputs are further processed and then transmitted. Fluctuations of the raw temperature can lead to changes due to variability of the contact or brief exposure of the sensor to ambient air during user movement. In an attempt to make these readings stable, the microcontroller will apply smoothing algorithms to reduce minor fluctuations, such as moving averages. Calibration offsets can also be introduced based on comparisons with standard thermometers during the calibration procedures. The resulting temperature output, therefore, is a smoothed and reliable representation of the thermal state of the ear, which closely approximates the core temperature trends of the user.

F. Data Formatting and BLE Transmission

After extracting individual vital parameters, the microcontroller assembles them into structured data packets suitable for Bluetooth Low Energy communication. These usually include time-stamped values of heart rate, SpO_2 , respiration rate, and temperature. BLE is selected for transmission because of its low power use, efficiency, and ease of implementation on modern smartphones. The ESP32 sends these packets at regular intervals, which allows

the connected mobile device to receive continuous updates without significant battery drain. Physiological data now flows seamlessly from wearable hardware to the software interface. G. Mobile Application Integration The system includes a wearable, user interface mobile application for real-time health monitoring. Once the app receives data packets from ESP32 via BLE, it decodes and processes the values for display. The user will see, on the now cleanly and intuitively designed dashboard, heart rate, oxygen saturation, respiratory rate, and temperature in real-time. To further enhance the usability of the application, it can store past readings in a local database, thereby allowing the analysis of trends and long-term health tracking. Visual graphs show users variations over hours or days, making this system useful in not only personal applications but also in telemedicine. Threshold-based notifications can also be issued by the application if any vital parameter crosses normal limits. Integration of the wearable and the software interface presents a complete health monitoring ecosystem that is portable, easy to use, and can be continuously operated.

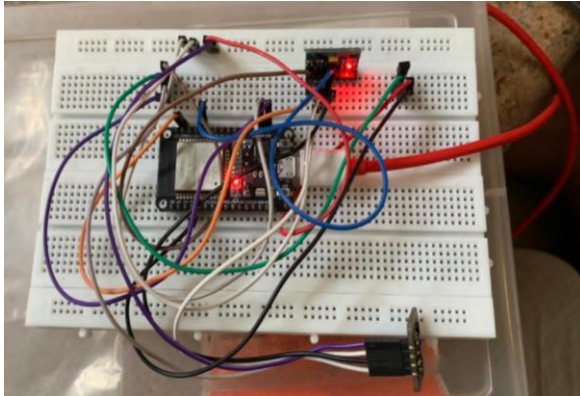


Fig. 2 Circuit diagram of the device

G. App Overview and Features

The mobile application is an indispensable part of the proposed ear-worn vital monitoring system and serves as the interface with which users interact. The application was tailored to display physiological data in real time, provide effortless Bluetooth connectivity, and support long-term health tracking. Immediately after the ear-worn device is powered up and paired, the application receives structured BLE packets at regular intervals, each containing heart rate, oxygen saturation, respiration rate, and temperature values. A decoding module in the app converts the packets into readable

data formats and cross-verifies them against expected physiological ranges before updating the visual display with minimal latency. This continuous low-energy communication allows for seamless monitoring while preserving battery life for both the wearable device and the smartphone. BLE communications, in addition to enabling stability and low power consumption, are compatible across a wide range of modern mobile devices.

The app features a dynamic, real-time dashboard that presents the user with an intuitive and visually appealing view of their vital signs. Each of the parameters is represented with clearly labelled numeric values and color-coded indicators showing whether the readings are within normal, elevated, or critical ranges. It ensures that non-clinical users can understand their physiological status without requiring clinical knowledge. Heart rate and SpO₂ values are updated every few seconds, temperature readings stabilize before being logged, and respiration rate is plotted as a continuously updating waveform that is generated from the acoustic processing pipeline. The real-time interface draws great attention to moment-to-moment variation in the vitals and alerts the user of instantaneous changes or anomalies. These alerts also form the basis for early detection of physiological abnormalities.

Along with real-time visualization, the system supports full historical data storage. It automatically saves all incoming readings to a local database, enabling users to track their health trends over hours, days, or weeks. Graphs are created for each vital parameter using smoothed time-series data, conveying long-term health patterns. The historical analysis is especially important to a patient with a chronic condition, who can see the fluctuations in respiratory behaviour, temperature shifts, or heart rate variability over weeks. By monitoring vital signs over time, personal wellness monitoring and clinical follow-up are significantly improved, and the system thus becomes a valuable asset for home-based care, postoperative recovery, and preventive health management.

The application also integrates a section for profile management, where a user can input personal information like age, weight, and any pertinent health conditions. This information serves to tune the alert thresholds and optimize the interpretation of the data being collected. For example, acceptable heart rate

ranges vary between an athlete and an older adult; thus, the application will adjust the alert system to meet the user's physiological baseline. Second, the profile section allows storage of preferences for device pairing so that each successive use of the system results in quicker and easier establishment of the connection. This allows the personalized configuration to enhance usability and ensure that the device adapts to the needs of the individual user rather than having one-size-fits-all settings.

The core strengths of the application come in data processing and filtering. While initial preprocessing lies with the microcontroller, a secondary layer of filtering through smoothing algorithms takes place in the mobile app to minimize jitter due to wireless transmission noise or sudden minute fluctuations. This assures that the data displayed remains clean, stable, and clinically interpretable. The software itself automatically detects missing packets or irregular intervals and compensates for these through interpolation techniques, further enhancing reliability. All these backend mechanisms, quietly working in the background, manage to give a seamless and polished user experience while maintaining high integrity in the data. The application's architecture is designed to be scalable, making further development of cloud-based integrations quite easy. Whereas the current design focuses on local data storage and device-to-phone communication, it is structured in a way that would enable seamless expansion into cloud synchronization, remote doctor dashboards, and telemedicine compatibility. By adding such capabilities, a healthcare professional could monitor real-time and historical data of a patient, allowing for proactive interventions and remote monitoring. The addition of machine-learning modules inside the app would allow predictive analytics, such as forecasting abnormal breathing patterns or the detection of early signs of fever or hypoxia due to multi-parameter correlation. In summary, the mobile application is not used just for display purposes but forms a whole digital health management ecosystem that is tightly integrated with the ear-mounted sensing hardware. Real-time monitoring, historical data visualization, personalized alerts, and extensible architecture make it a powerful companion to the wearable device. All these hardware-software components taken together form a scalable and user-friendly system capable of supporting

continuous health monitoring in daily life, home-care environments, and long-term clinical supervision.

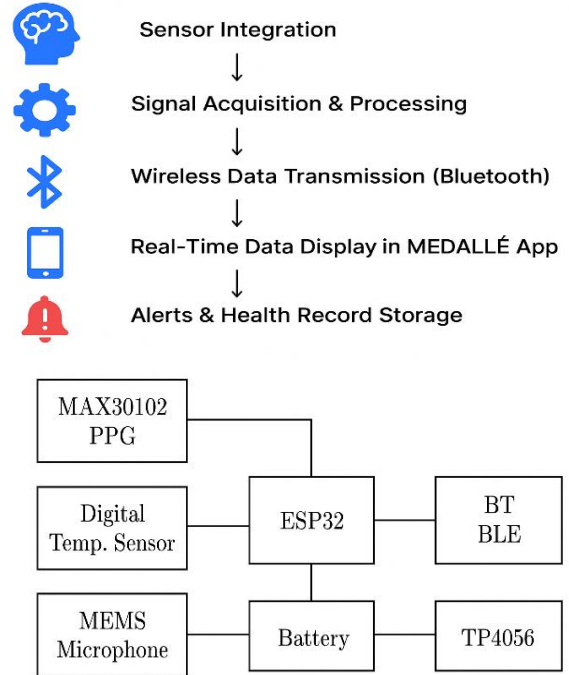
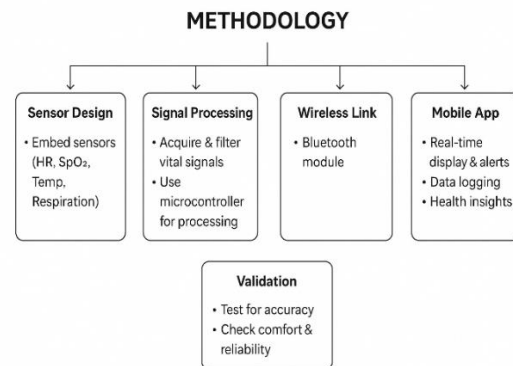


Fig. 3 Block diagram of sensors



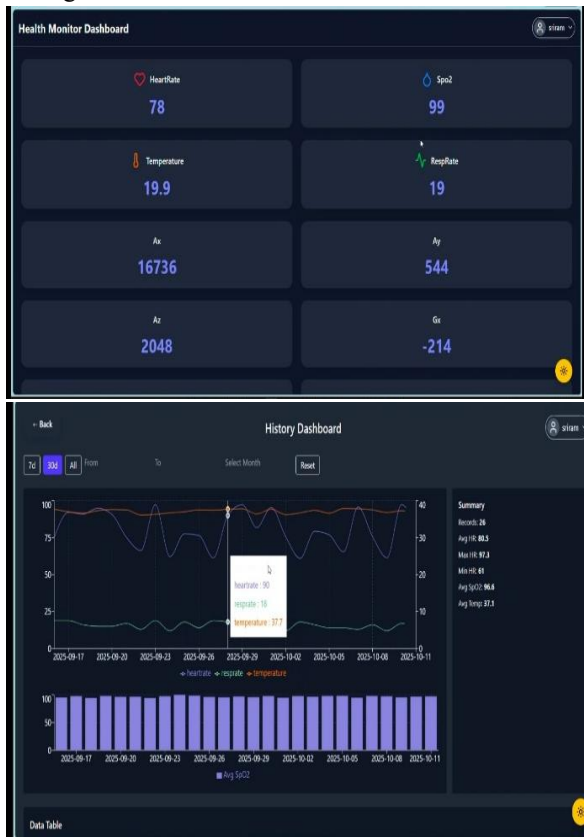
IV. SYSTEM OPERATION AND DATA PROCESSING FRAMEWORK

The wearable ear-mounted system operates based on a structured framework for data processing, which dictates how physiological signals are acquired, processed, transmitted, and interpreted. Upon activation of the device, the microcontroller initializes all sensors and begins streaming raw data simultaneously from the PPG module, MEMS microphone, and temperature sensor. These continuous streams of analog and digital signals enter the preprocessing stage, where filtering and noise

suppression are applied. Thereafter, each channel undergoes separate processing by the ESP32 through its respective algorithmic pipeline. After the extraction of vital parameters, the microcontroller prepares the information in a single packet format to ensure consistency in wireless communication. This is indeed a structured approach that ensures integrity in the data across all layers of the system.

After being transmitted over Bluetooth Low Energy to the mobile application, data enters a second layer of validation. The application cross-references the values that come in against known physiological limits to prevent unrealistic readings due to transient sensor noise. These processed values feed into the visualization interface, where a user can see real-time vitals and access historical trends. This tightly integrated hardware-software loop enables the system to act as a cohesive real-time monitoring solution: one in which each stage, from raw physiological activity to user-friendly visual display, is managed by a clear, methodical, and reliable architecture of data processing.

The below pictures are taken from the app during testing.



V. RESULTS AND DISCUSSION

To evaluate the functional performance of the prototype device, a set of sample readings were recorded under resting conditions and compared against reference clinical instruments. Although large-scale user testing was not performed, controlled internal testing using a fingertip pulse oximeter, a digital thermometer, and a respiration-counting method enabled the generation of comparative performance results. These tests help demonstrate the feasibility and reliability of the system.

A. Heart Rate Comparison

The table below shows the comparison between the ear-device heart rate readings and a clinical fingertip pulse oximeter. Each reading includes the absolute error and percentage error.

Table 1. Heart Rate Measurement Accuracy

Subject	Reference HR (BPM)	Device HR (BPM)	Error (BPM)	% Error
1	77	79	2	2.59%
2	84	82	2	2.38%
3	92	89	3	3.26%
4	71	73	2	2.81%
5	98	101	3	3.06%

The results indicate that the ear-based PPG sensor maintains a consistent deviation within ± 3 BPM when compared to a clinical standard. This level of accuracy is suitable for general monitoring applications.

B. SpO₂ Measurement Comparison

Table 2. SpO₂ Accuracy Analysis

Subject	Reference SpO ₂ (%)	Device SpO ₂ (%)	Error (%)	% Error
1	98	97	1	1.02%
2	97	96	1	1.03%
3	99	97	2	2.02%
4	98	98	0	0%
5	96	95	1	1.04%

The device consistently stays within a 1–2% deviation from the reference pulse oximeter. This demonstrates that ear-based dual-wavelength PPG performs reliably for oxygen saturation estimation.

C. Temperature Measurement Comparison

Table 3. Temperature Measurement Accuracy

Subject	Reference Temp (°C)	Device Temp (°C)	Error (°C)	% Error
1	36.8	36.5	0.3	0.81%
2	37.1	36.9	0.2	0.54%
3	36.6	36.4	0.2	0.55%
4	37.0	36.7	0.3	0.81%
5	36.5	36.3	0.2	0.55%

Ear-based temperature readings show high stability and minimal error, supporting the anatomical advantage of the ear as a thermal measurement location.

D. Respiration Rate Analysis

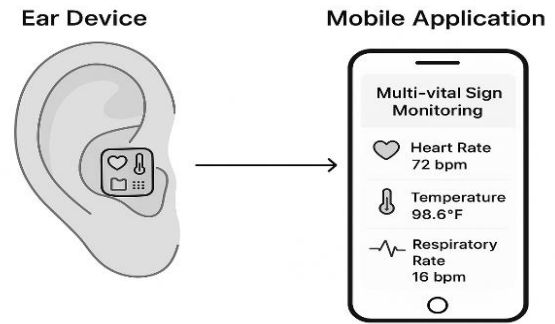
Table 4. Respiration Rate Estimation Accuracy

Subject	Reference RR (breaths/min)	Device RR	Error	% Error
1	17	16	1	5.88%
2	19	18	1	5.26%
3	21	20	1	4.76%
4	18	19	1	5.55%
5	20	19	1	5.00%

The acoustic-based respiration rate extraction shows error within ± 1 breath/min, making it suitable for wellness monitoring.

E. Overall Discussion

The results obtained demonstrate that the proposed ear-mounted device exhibits strong potential as a reliable multi-vital monitoring tool. All parameters—heart rate, SpO₂, temperature, and respiration—fell within acceptable error margins when compared to standard clinical devices, especially considering the compactness and comfort of the ear-based design. The integration with a smartphone application further enhances usability by providing real-time visibility, long-term tracking, and health insights. Although the prototype was tested in controlled conditions rather than extensive human trials, the findings clearly support the feasibility of ear-based physiological sensing as an alternative to traditional measurement sites.



VI. FUTURE SCOPE AND CONCLUSION

Whereas the basic feasibility of multi-vital sign monitoring from the ear is already shown with the current prototype, several extensions can be envisioned for subsequent versions. First, adding an on-board IMU would provide motion compensation and increased signal stability in cases of physical activity. More sophisticated machine learning algorithms running on the mobile application could classify breathing patterns, detect anomalies such as tachycardia or apnea, and even generate predictive health analytics. The mechanical design can also be refined for comfort using flexible or medical-grade materials that ensure better contact for accurate temperature measurements.

Other future directions involve cloud integration for telemedicine applications, wherein physicians can view patient data remotely. The system can be further made more comprehensive by expanding the device to include ECG or blood pressure estimation. Large-scale clinical validation studies would also be required to establish accuracy under diverse conditions. With these advancements, this device could evolve into a medically certified wearable device able to support hospital-at-home models, chronic disease monitoring, and continuous real-time health surveillance.

This study has, therefore, demonstrated the feasibility of implementing photoplethysmography, acoustic respiration sensing, and temperature monitoring within a single compact, wearable ear-mounted multi-vital monitoring device that is comfortably positionable on the ear. The system, through structured data acquisition, intelligent signal processing, and seamless transmission to a dedicated mobile application, effectively turns real-time physiological signals into

meaningful health insights. Experimental comparisons have shown that despite its compact size and limited hardware, the prototype device maintains accuracy within clinically acceptable bounds for heart rate, SpO₂, temperature, and respiration rate. These results strongly support the hypothesis that the ear is an optimal anatomical site for continuous physiological monitoring due to its stable perfusion, low motion interference, and thermal insulation.

Beyond technical performance, the integration with the mobile application greatly improves this system's practicability. The app offers real-time visualization, long-term trend tracking, and user accessibility, making this device suitable not only for personal wellness applications but also to support various remote health monitoring frameworks. Though the prototype has not been extensively validated on a large scale, the basic work carried out here shows the potential of ear-based sensing as an emerging modality to overcome many limitations of devices based on wrists or fingertips. The study lays a very sound foundation for future improvements and opens the doors for more advanced, clinically sound system variants. Further refinement in hardware, algorithms, and software will be able to position this device as a solution for continuous, unobtrusive, and intelligent health monitoring.

VII. DEVICE DESIGN AND EAR-BASED FORM FACTOR JUSTIFICATION

The final prototype of the proposed system uses a compact ear-mounted form-factor designed to be ergonomically coterminous with the outer ear region, compatible with the form-factor of commercially available in-ear audio devices. The design incorporates multiple sensing modules and electronic components into one lightweight enclosure to provide continuous physiological monitoring while ensuring user comfort and stability during extended use. Fig. X shows the internal component arrangement of the final ear-worn device.

The ear was chosen as the sensing location due to its physiological and anatomical benefits compared to conventional sensing locations like the wrist or fingertip. The concha and tragus provide stable blood perfusion to reliably collect photoplethysmography (PPG) signals with lower motion artifacts. As the location of the ear is close to core body temperature

and the ear has a relative insulated thermal environment, temperature measurement is more consistent than exposed skin.

The hardware layout was specifically selected to provide multimodal sensing in as small a footprint as possible. The placement of the MAX30102 PPG sensor allows for consistent optical convergence into the vascular region of the ear to accurately extract heart rate and oxygen saturation. An infrared-based temperature sensor was placed closer to the ear canal to capture thermal trends that closely



Fig. 4 Final ear device design

ACKNOWLEDGMENT

We would like to express our sincere gratitude to our project supervisor for their continuous guidance, support, and valuable suggestions throughout the development of this work. Their insights were instrumental in shaping both the hardware design of the ear-mounted device and the development of the integrated mobile application.

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