Portable Non – Invasive Device for ECG and EMG Monitoring

Dayananda L N [1], Kiran Kumar M [2], Nikhil R Shetty [3], Manoj Benachina Maradi [4], Chidambar V G [5]

Department of Electronics and Communication Engineering, Jyothy Institute of Technology Bangalore , India

[1] dayananda.ln@jyothyit.ac.in
[2] kirankumar.m233@gmail.com
[3] nikhilraghushetty08122002gmail.com
[4] manojbmaradi2021@gmail.com
[5] chidambar0311@gmail.com

***Abstract*— This project proposes the design and implementation of a portable, non-invasive ECG and EMG monitoring system using the ESP32-S3 microcontroller. The system is capable of capturing and displaying real-time bioelectrical signals from the human body using two dedicated sensors—an AD8232 module for electrocardiogram (ECG) signal acquisition and a modular EMG sensor for muscle activity monitoring. The ESP32-S3's built-in ADC is used to digitize the signals, which are then processed and displayed as scrolling waveforms on a 320×240 SPI TFT display. A push-button interface is incorporated to switch between ECG and EMG modes, allowing users to monitor both heart and muscle signals dynamically. Each mode is visually distinguished with color-coded waveforms—red for ECG and green for EMG—ensuring clarity and ease of interpretation. Additionally, the system logs the sensor values to the serial monitor in real time for further analysis and debugging. The entire hardware is compactly assembled on an acrylic casing, providing a professional and ergonomic enclosure. This cost-effective solution demonstrates a reliable and user-friendly approach to basic bio signal monitoring and is suitable for applications in academic research, physiotherapy, wearable health tech development, and biomedical education.**

Keywords—*ESP32-S3, ECG Monitoring, EMG Signal, Non-Invasive Sensors, Biomedical Signal Acquisition, Real-Time Visualization, TFT Display, Portable Monitoring System, IoT Health Applications.*

I. INTRODUCTION

In recent years, the increasing prevalence of chronic diseases, rising healthcare costs, and the demand for personalized medical technologies have driven the development of compact, non-invasive health monitoring systems. Real-time acquisition and interpretation of physiological signals are critical for early diagnosis, rehabilitation, and continuous health assessment. Among these signals, electrocardiogram (ECG) and electromyogram (EMG) measurements serve as vital indicators of cardiac and neuromuscular activity, respectively. Traditional clinical-grade monitoring equipment, while accurate, is often expensive, bulky, and impractical for continuous or remote applications.

This paper presents a Portable Non-Invasive Device for ECG and EMG Monitoring, an embedded biomedical system designed to dynamically capture and visualize both cardiac and muscular bioelectric signals using low-cost, off-the-shelf components. The core of the system is the ESP32-S3 microcontroller, which features integrated Wi-Fi/Bluetooth support and high-performance ADCs. The device incorporates an AD8232 ECG sensor and a modular EMG sensor, interfaced with a 2.4-inch SPI-based TFT display for real-time graphical rendering of signal waveforms. Signal acquisition and mode switching are controlled via a tactile push button, with display updates and signal differentiation (e.g., colour coding) handled programmatically.

Firmware is written in MicroPython and deployed through the Thonny IDE, ensuring lightweight memory usage and rapid prototyping capabilities. The hardware is mounted in a custom acrylic casing designed for ergonomic placement of components: the display is front-facing for clear visualization, sensors are side-mounted for ease of electrode connection, and the ESP32-S3 is secured on a general-purpose board at the rear. This modular design enables streamlined signal routing, mechanical robustness, and enhanced portability.

This work demonstrates a technically viable and economically efficient alternative to commercial monitoring systems, particularly suitable for academic environments, physiotherapy labs, home health tracking, and wearable biomedical research.

Key Contributions:

- Dual-Mode Signal Acquisition: Enables seamless monitoring of both ECG and EMG signals using a single embedded system with dynamic mode-switching via user input.
- Compact Embedded Architecture: Integrates sensors, microcontroller, and display within a custom ergonomic acrylic enclosure optimized for usability and portability.
- Real-Time Visualization & Open-Source Development: Offers color-coded waveform rendering on a TFT screen using Micro-Python, making it accessible for educational and prototyping applications.

II. SYSTEM DESIGN AND METHODOLOGY

A. *System design and setup*

The device is designed to offer a compact, real-time bio-signal acquisition and visualization solution using a custom acrylic stand for ergonomic and user-friendly integration. The system is mechanically housed on a custom designed acrylic stand, where:

- The TFT display (ILI9341) is mounted on the front-facing angled panel for easy waveform viewing.
- The ESP32-S3 module is placed securely on the base of the stand, ensuring stable USB connectivity and centralized control.
- The ECG sensor (AD8232) and EMG sensor are attached to the left and right sides of the stand, respectively, with electrode cables routed cleanly for patient connection.

- A push-button is embedded on the front base, just below the display, to toggle between ECG and EMG modes.

Fig.1 The system mounted upon the acrylic stand

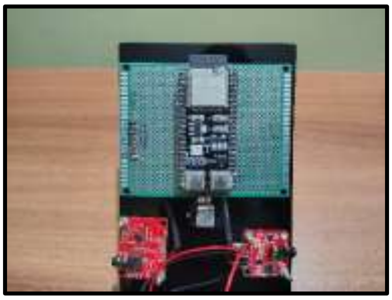

Fig. 2 The mounting of the sensors and the ESP32-S3

B. *Methodology*

The development of the proposed portable biomedical monitoring device follows a structured engineering workflow, encompassing hardware integration, signal acquisition, mode-switching logic, data visualization, and validation. Each phase of the methodology is elaborated below to reflect the embedded system design and its biomedical application. The hardware integration process begins with the mechanical assembly of the system components on a custom-designed acrylic stand.

The core processing unit, the ESP32-S3 microcontroller, is mounted on a general-purpose board (GPB) affixed to the rear of the display module. The AD8232 ECG sensor and a standard EMG Analog sensor module are securely attached to the side panels to allow convenient connection of surface electrodes. A 2.4-inch SPI-based TFT display is front-mounted for optimal visibility, and a momentary push-button switch is positioned ergonomically for easy mode selection. Electrical interconnections include routing the ECG and EMG sensor outputs to dedicated Analog-to-digital converter (ADC) input pins on the ESP32-S3. The TFT display is interfaced via the SPI communication bus, while the push-button is connected to a general-purpose input/output (GPIO) pin configured for interrupt-driven input detection. All modules share a regulated 3.3 V power rail and common ground.

Once the system is assembled, the signal acquisition routine is implemented through the ESP32-S3's onboard ADCs. These peripherals sample the analog voltage levels from the ECG and EMG sensors at an appropriate frequency to capture the respective signal dynamics. The sampled data is processed and mapped to pixel coordinates on the display, enabling real-time waveform generation. The mode-switching logic is realized using a hardware interrupt mechanism tied to the push-button. When activated, the interrupt service routine toggles a system flag that controls which sensor is currently active. Accordingly, the software reconfigures the input channel, display color scheme, and signal scaling parameters, allowing the user to seamlessly transition between ECG and EMG monitoring modes without system reboot. For real-time data visualization, a dedicated graphics driver renders the acquired signal samples as continuous, scrolling waveforms on the TFT display. Each mode is assigned a distinct waveform color—blue for ECG and green for EMG—to provide intuitive visual differentiation. Simultaneously, the raw data values are logged to the ESP32-S3's serial output, allowing developers or clinicians to inspect the numerical signal data on a connected terminal or integrate the output with a PC-based analysis tool.

The final stage involves testing and validation of the system's accuracy and reliability. The output waveforms displayed by the device are compared against those obtained from a certified clinical-grade biomedical acquisition system. Parameters such as signal shape, response time, and noise rejection are evaluated to ensure the prototype delivers consistent and interpretable data suitable for academic, experimental, or personal healthcare applications.

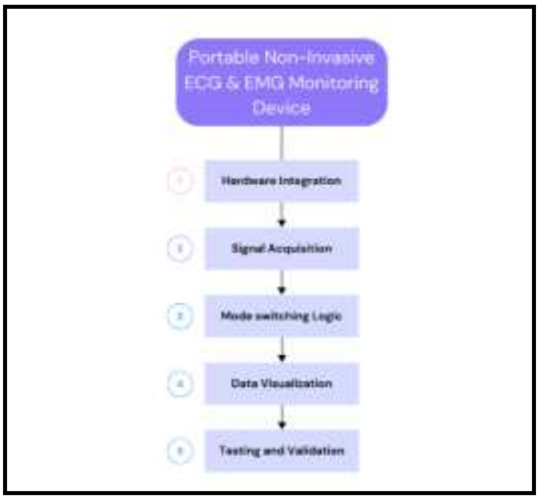

Fig. 3 Flowchart of methodology

III. IMPLEMENTATION

A. *Hardware Implementation*

The hardware setup for this project is designed to be compact, user-friendly, and efficient, enabling real-time monitoring and visualization of biomedical signals. At the heart of the system lies the ESP32-S3 microcontroller, which offers powerful processing capabilities and built-in wireless connectivity, making it ideal for portable health monitoring applications. It interfaces with the AD8232 for ECG signal acquisition and a standard EMG sensor to capture vital electrical signals from the human body.

A 2.4-inch SPI-based TFT display renders the waveforms in real-time, offering immediate visual feedback to the user. All components are arranged ergonomically onto an acrylic stand, with the ESP32-S3 housed on the back of the display mounted on a General-Purpose board, sensors placed on the sides for electrode connection, and the display prominently on the front, ensuring reliable data acquisition and a smooth user experience in a portable format.

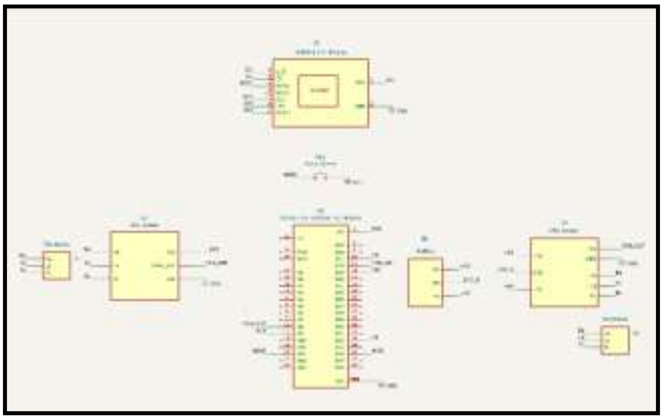

Fig. 4 Block diagram of ECG and EMG monitoring

B. *Software Implementation*

The software development for the proposed biomedical monitoring system was conducted using Micro-Python within the Thonny Python IDE. This development environment was selected for its ease of use, integrated debugging tools, and compatibility with the ESP32-S3 microcontroller. The codebase was modularly structured to handle ADC configuration, TFT display rendering, and mode-switching logic for ECG and EMG signals.

Thonny IDE simplifies embedded programming by providing a lightweight graphical interface that allows code editing, execution, and serial communication all within a single workspace. This is especially beneficial when working with resource-constrained microcontrollers like the ESP32-S3. The platform supports a real-time REPL (Read-Eval-Print Loop) and serial monitor, which were instrumental in debugging and validating sensor outputs during development.
The firmware was implemented using Micro-Python, a lightweight implementation of the Python 3 language designed for embedded systems. It enables direct manipulation of hardware peripherals using high-level syntax. This allows developers to rapidly prototype, iterate, and deploy code to the microcontroller without the overhead of traditional C/C++ toolchains.

The software initialization sequence includes setting up the SPI interface for communication between the ESP32-S3 and the 2.4-inch ILI9341 TFT display. Display parameters such as screen resolution, rotation, and baud rate are configured to ensure smooth graphical rendering. The ADC pins are initialized for capturing analog signals from the ECG and EMG sensors, and signal attenuation is calibrated using built-in Micro-Python methods to ensure accurate voltage scaling.

A key component of the software design is the interrupt-based mode-switching logic, where a push-button connected to a GPIO pin is used to toggle between ECG and EMG modes. This toggle operation updates the display context and reconfigures the active ADC channel. A continuous loop reads analog values, processes them into screen coordinates, and updates the display buffer with a scrolling waveform in real time. Each mode is color-coded to enhance user interaction—red waveform for ECG and green for EMG. This visual distinction is rendered directly using Micro-Python graphics libraries for the ILI9341 driver. Additionally, signal values are echoed to the serial monitor for diagnostic and debugging purposes. This efficient, high-level software approach not only facilitates rapid development but also ensures that future enhancements such as Wi-Fi-based data transmission, onboard analytics, or cloud integration can be seamlessly implemented using Micro-Python extended library support. As a result, the system remains both accessible and extensible for a wide range of research and educational applications.

Fig. 5 A Snapshot of the Thonny Python IDE Interface

IV. RESULTS AND DISCUSSION

The developed system was tested in both controlled indoor conditions and semi-mobile use to evaluate its capability in capturing and displaying real-time ECG and EMG signals. Upon deployment, the TFT display provided smooth horizontal scrolling of waveforms with distinct color-coded visualization—red for ECG and green for EMG—allowing the user to easily identify different bio-signals. A push-button interface enabled reliable switching between modes without interrupting signal acquisition, validating the system's real-time responsiveness.

The ECG waveform captured using the AD8232 sensor successfully demonstrated identifiable cardiac patterns, including the QRS complex. Although the sampling rate (~50 Hz) and ADC resolution (12-bit) limited clinical precision, the system effectively indicated cardiac rhythm and R-peaks, making it suitable for basic heart rate monitoring and educational demonstrations. Minor baseline noise was observed, which can be further reduced with digital filtering in future iterations.

The EMG signals showed high-frequency bursts typical of muscular activity. The waveform amplitude reflected intensity of muscle contractions with full-scale ADC utilization. While raw

EMG signals appeared more erratic due to their inherent nature, the system was able to display them accurately in real time. The threshold-based peak detection algorithm also performed reliably, marking high-amplitude signal events clearly on the waveform.

Physically, the use of an acrylic stand proved to be both compact and ergonomic. The tilted front face allowed comfortable viewing of the waveform, while the base supported stable mounting of the ESP32 module and push-button. The side-mounted ECG and EMG sensors ensured easy electrode connection and cable routing.

Overall, the system demonstrated a cost-effective, portable, and functional platform for non-invasive physiological signal monitoring, suitable for academic, demonstrative, and early-stage health tech prototyping purposes.

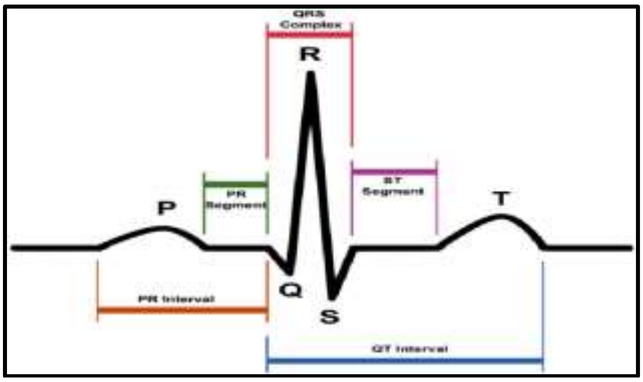

Fig. 6 ECG Waveform Characteristics

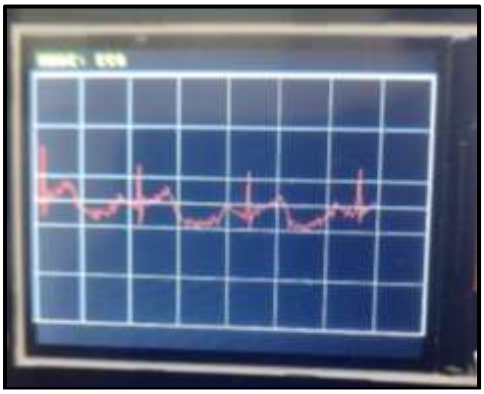

Fig. 7 ECG Waveform displayed on the device

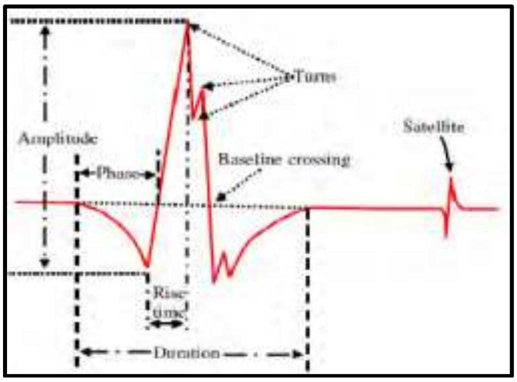

Fig.8 EMG Waveform Characteristics

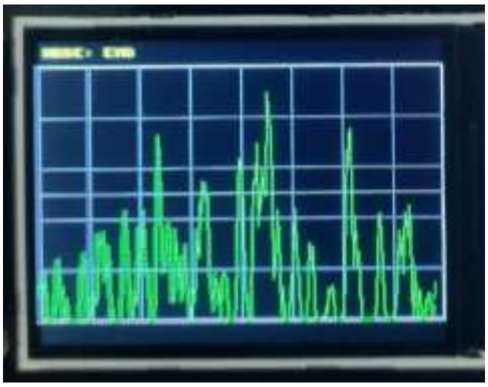

Fig. 9 EMG Waveform displayed on the device

V. CONCLUSION

This paper presents the design and realization of a low-cost, portable, and non-invasive physiological signal monitoring system using the ESP32-S3 microcontroller. The system is capable of capturing and displaying both ECG and EMG waveforms in real time using analog sensors and a colour TFT display. A simple push-button interface allows the user to toggle between ECG and EMG modes, providing a flexible platform for multi-signal observation within a compact form factor.

The hardware is mounted on a custom acrylic stand, ensuring both stability and ease of use. The front-facing display allows for intuitive visualization, while the base securely holds the microcontroller and button, and the sides accommodate the ECG and EMG sensor modules. The visualization component features scrolling waveforms, color-coded signal modes, and real-time peak detection, effectively demonstrating critical aspects of human bioelectric activity. The ECG waveforms captured exhibited identifiable QRS complexes, and the EMG signals responded well to muscular activity, confirming the system's functional reliability.

Although the system is not intended for clinical diagnostics, it serves as an excellent educational tool and a starting point for further development in wearable health technologies. Potential future improvements include implementing digital signal filtering, heart rate computation, data storage, and extended sensor support. Overall, the system demonstrates an effective blend of embedded system design and biomedical signal acquisition, making it valuable for academic projects, prototyping, and introductory research in biomedical electronics.

VI. FUTURE WORK

The successful implementation of this portable, non-invasive ECG and EMG monitoring device establishes a foundational platform for further research and development. As healthcare increasingly integrates with the Internet of Things (IoT), wearable electronics, and data-driven diagnostics, there exists considerable scope to enhance the current system both in terms of hardware capability and software functionality.

One of the most promising areas for future expansion involves the incorporation of wireless communication protocols such as Wi-Fi and Bluetooth. This would enable real-time data transmission to external devices, such as smartphones or cloud-based platforms, thereby supporting remote health monitoring, telemedicine applications, and clinical diagnostics in decentralized environments. Through seamless wireless integration, continuous patient monitoring could be achieved without tethering to a local display or computer. Another critical enhancement involves data logging and long-term storage.

By integrating an SD card module or cloud synchronization capability, the device could store bio-signal data over extended periods. This would allow for longitudinal health assessments, retrospective analysis, and predictive diagnostics using signal trend analytics. Furthermore, such functionality could serve as a valuable tool for medical professionals in identifying arrhythmias, neuromuscular anomalies, or rehabilitation progress in patients. The development of a mobile application interface is also a key avenue for improving usability and accessibility. A companion mobile app could offer real-time signal visualization, customizable alerts for threshold breaches, and automated reporting features. This would enhance the user experience and provide a more intuitive way for patients and healthcare providers to interact with the system, making it especially suitable for non-specialist users in home healthcare scenarios.

Additionally, the signal acquisition process could be refined through the implementation of advanced digital filtering and adaptive signal processing techniques. Methods such as moving average filters, Butterworth filters, or machine learning-based noise classification could substantially enhance signal fidelity. These improvements would reduce motion artifacts and baseline drift, thereby improving clinical relevance and diagnostic accuracy.

To extend system versatility, multi-channel acquisition could be explored, allowing simultaneous ECG and EMG monitoring or even the addition of other vital signs such as oxygen saturation (SpO_2), temperature, or respiration rate. This would transform the device from a dedicated bio-signal monitor into a comprehensive portable health diagnostic unit. Finally, future iterations of the device could adopt ultra-low-power microcontrollers, energy harvesting modules, or battery optimization algorithms to support long-term deployment in wearable applications. This would be especially relevant for continuous health tracking in fitness monitoring, elderly care, and remote patient surveillance.

REFERENCES

[1] D. Yi, F. Binwen, K. Xiaoming, and M. Qianqian, "Design and Implementation of Mobile Health Monitoring System Based on MQTT Protocol," in *Proc. IEEE*, 2016, doi: 10.1109/ICCCNT.2016.7566859.

[2] L. D. Rumpa, S. Suluh, I. H. Ramopoly, and W. Jefriyanto, "Development of ECG sensor using Arduino Uno and e-health sensor platform: mood detection from heartbeat," *J. Phys.: Conf. Ser.*, vol. 1528, p. 012043, 2020, doi: 10.1088/1742-6596/1528/1/012043.

[3] S. T. Alam, M. M. Hossain, M. D. Rahman, and M. K. Islam, "Towards Development of a Low Cost and Portable ECG Monitoring System for Rural/Remote Areas of Bangladesh," *Int. J. Image, Graphics and Signal Process.*, vol. 10, no. 5, pp. 24–32, May 2018, doi: 10.5815/ijigsp.2018.05.03.

[4] M. V. Dole and V. V. Yerigeri, "ESP8266 based health monitoring system using Arduino," *Int. Res. J. Eng. Technol. (IRJET)*, vol. 7, no. 7, pp. 4071–4079, Jul. 2020.

[5] Md. Rahman, Y. Li, T. Nabeed, and Md. T. Rahman, "Remote monitoring of heart rate and ECG signal using ESP32," in *Proc. Int. Conf. Adv. Electr., Mach. Control Syst. Eng. (AEMCSE)*, 2021, pp. 604–610, doi: 10.1109/AEMCSE51986.2021.00127.

[6] W. Guan, "An electrocardiogram monitoring device based on STM32," *arXiv preprint* arXiv:2411.06962, 2024, doi: 10.48550/arXiv.2411.06962.

[7] C. Bhattarai, S. Yadav, and S. Koirala, "IoT based ECG using AD8232 and ESP32," *Nepal J. Sci. Technol.*, vol. 21, pp. 115–121, 2022, doi: 10.3126/njst.v21i2.62361.

[8] J. Heaney, J. Buick, M. U. Hadi and N. Soin, "Internet of Things-Based ECG and Vitals Healthcare Monitoring System," *Micromachines*, vol. 13, no. 12, p. 2153, Dec. 2022. doi: 10.3390/mi13122153.

[9] H. R. Mahmood, M. K. Hussein, and R. A. Abedraba, "Development of a Low-Cost Bio signal Acquisition System for ECG, EMG and EOG," *Wasit Journal of Engineering Sciences*, vol. 10, no. 3, pp. 191–202, 2022. doi: 10.31185/ejuow.Vol10.Iss3.352.