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BIO-MEDICAL SIGNAL INSTRUMENTATION

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Abstract: This project focuses on designing and building a compact, multi-parameter biomedical monitoring system using the ESP32 microcontroller. The idea behind this work was to create a simple, low-cost device that can continuously track important health parameters, especially in situations where access to advanced medical equipment is limited or not practical.

To achieve this, the system combines several commonly used biosensors. A MAX30102 module is used to measure heart rate and blood oxygen levels (SpO_2) using photoplethysmography (PPG). For monitoring heart activity, an AD8232-based ECG sensor is included, while muscle signals are captured using a basic EMG sensor. In addition, a temperature sensor such as the DS18B20 is used to keep track of body temperature. Bringing all these sensors together allows the system to monitor multiple physiological signals at the same time.

Both analog and digital signals from these sensors are handled by the ESP32. For signals like ECG and EMG, which are more sensitive to noise, simple signal conditioning techniques were applied. This included basic amplification and RC filtering to reduce interference from sources like power-line noise and body movement. The ESP32 reads these signals through its ADC channels, while digital data from the MAX30102 is obtained via I2C communication. Depending on the type of signal, a sampling rate between 100 and 500 Hz was used. To further improve signal quality, lightweight software filters such as moving average and bandpass filters were implemented.

The system is capable of processing multiple inputs almost in real time, with reasonable synchronization across different channels. The measured values—such as heart rate (in BPM), SpO_2 levels, ECG waveform, EMG activity, and temperature—are displayed instantly on a small LCD or OLED screen. This makes it easy to view the data directly on the device without needing any external system.

To extend its functionality, the ESP32's built-in Wi-Fi is used to send data to cloud platforms like Thing Speak or through an MQTT-based setup. This allows users or healthcare providers to monitor the readings remotely from anywhere with an internet connection. The communication is designed to be lightweight so that it does not significantly affect performance or power consumption. One of the main strengths of this system is its affordability and simplicity. Since it uses easily available components, the overall cost remains low, making it suitable for home monitoring, educational projects, or basic telehealth applications.

Data transmission to the cloud was also reliable, with only minor delays observed. However, it is important to note that this system is intended as a proof-of-concept and is not a replacement for certified medical equipment. Overall, this project demonstrates how microcontrollers like the ESP32, when combined with low-cost sensors and IoT capabilities, can be used to build practical and accessible health monitoring solutions.

Keywords:
Biomedical Signal Processing, ESP32 Microcontroller, MAX30102, ECG (Electrocardiogram), EMG (Electromyography), SpO_2 Monitoring, Heart Rate Monitoring, Real-Time Health Monitoring, Internet of Things (IoT), Remote Patient Monitoring, Wearable Health Devices, Signal Conditioning, Embedded Systems, Low-Cost Healthcare Solution, Cloud-Based Monitoring.

I. Introduction

Visually Keeping track of a person's health between doctor visits has always been difficult, and in many cases, it becomes a serious concern. For individuals living with chronic conditions such as diabetes, heart disease, or respiratory disorders, waiting for the next scheduled check-up to identify a problem can be risky. In rural or underserved areas, the situation is even more challenging, as regular access to healthcare facilities is often limited.

This gap in continuous monitoring is what inspired this project. Instead of building a device that focuses on just one parameter, the aim was to create a system capable of monitoring multiple vital signs at the same time, while still being affordable and easy to use outside a clinical environment.

At the core of the system is the ESP32 microcontroller, chosen for its ability to handle both data processing and wireless communication within a single, low-cost platform. The device integrates four sensors: a MAX30102 module for measuring heart rate and blood oxygen saturation (SpO_2), an ECG sensor to capture the electrical activity of the heart, an EMG sensor for detecting muscle signals, and a temperature sensor to monitor body temperature. Together, these sensors provide a broader and more meaningful view of a person's physiological condition in real time.

The system is designed to be practical and user-friendly. Measurements are displayed instantly on a small screen, allowing immediate feedback. At the same time, the data is transmitted wirelessly to a cloud platform, making it possible for caregivers, doctors, or even the users themselves to monitor health parameters remotely. This flexibility allows the system to be used in different settings, including homes, small clinics, or even educational environments.

A key focus throughout the design was to keep the system simple and affordable. While there are many advanced medical monitoring devices available, they are often expensive, bulky, and require trained professionals to operate. In contrast, this project explores the possibility of creating a device that is accessible to students, usable at home, and practical for low-resource healthcare settings.

It is important to note that this system is not intended to replace professional medical equipment. Instead, it demonstrates how readily available IoT components can be combined in a thoughtful way to create a functional and accessible health monitoring solution. In doing so, it highlights a step toward more practical, everyday healthcare technologies.

II. LITERATURE REVIEW

Wearable Over the past few years, there's been a growing push to make health monitoring more accessible — not just in hospitals, but in everyday life. With the rise of remote patient care and the desire for continuous health tracking, researchers and engineers have been looking for ways to build systems that are affordable, portable, and practical for real-world use. Traditional monitoring equipment tends to be bulky, expensive, and confined to clinical settings, which makes it out of reach for most people outside a doctor's office.

Early efforts in this space largely focused on tracking just one thing at a time — heart rate, or maybe body temperature. These systems were a decent starting point, but they only tell part of the story when it comes to a person's health. That's why more recent work has moved toward multi-parameter systems — devices that can monitor several physiological signals at once, giving a much more complete picture.

Microcontrollers like the ESP32 and Arduino have become go-to choices for this kind of work. They're cheap, relatively easy to work with, and come with built-in wireless communication, which makes them well-suited for IoT-based applications. On the sensor side, technologies like PPG sensors — used to measure SpO_2 and heart rate — and compact ECG modules have matured enough that integrating them into a single, unified platform is now genuinely feasible.

That said, building a reliable system isn't without its challenges. Signal noise, power consumption, accuracy, and consistent data transmission are all problems that researchers are still actively working through. This survey looks at where the field currently stands and makes the case for a compact, multi-parameter, IoT-enabled monitoring system — which is exactly what the proposed work aims to deliver.

III. Methodology

Requirement Analysis: The system was designed to monitor multiple physiological parameters, including heart rate, SpO_2, ECG, EMG, and body temperature, using a single platform. Suitable sensors were selected to ensure a balance between accuracy, cost, and availability. The ESP32 microcontroller was chosen for its ability to handle real-time processing and support wireless communication. The software requirements included signal acquisition, basic filtering, and real-time data display, along with cloud connectivity for remote monitoring. Additional considerations such as low power consumption, compact design, ease of use, and scalability were also taken into account during the system development.

Design of Sensing Module:

Selection of Sensors: Appropriate biosensors were selected to measure different physiological parameters effectively. The MAX30102 sensor is used for monitoring heart rate and SpO_2 using PPG techniques. An ECG sensor is included to capture electrical activity of the heart, while an EMG sensor detects muscle signals. A temperature sensor is used to measure body temperature. These sensors were chosen based on their compatibility with the system, cost-effectiveness, availability, and ability to provide reliable data for real-time monitoring applications.

Sensor Integration: All All selected sensors are integrated with the ESP32 microcontroller to form a unified system. The MAX30102 sensor communicates digitally through the I2C protocol, ensuring efficient data transfer. In contrast, ECG and EMG sensors produce analog signals, which are connected to the ESP32's ADC pins for processing. Proper wiring and interfacing techniques are used to ensure stable communication between components. This integration allows the microcontroller to collect data simultaneously from multiple sensors and process it efficiently.

Signal Acquisition: The sensors continuously capture physiological signals from the human body in real time. Each sensor operates according to its sensing principle, collecting data such as heart rate, oxygen saturation, electrical cardiac signals, muscle activity, and temperature. These signals are gathered without interruption to ensure continuous monitoring. Real-time acquisition enables the system to detect any changes in physiological conditions immediately, making it suitable for applications that require constant health tracking and quick response.

Signal Conditioning: Analog signals obtained from ECG and EMG sensors are often affected by noise due to motion, environmental interference, and electrical disturbances. To improve signal quality, basic signal conditioning techniques are applied. This includes amplification to strengthen weak signals and filtering to remove unwanted noise components. RC filters are typically used to reduce power-line interference and other disturbances. These conditioning steps ensure that the signals become clearer and more reliable before being processed by the microcontroller.

Data Conversion: The After signal conditioning, the analog signals from ECG and EMG sensors are converted into digital form using the built-in Analog-to-Digital Converter (ADC) of the ESP32. This conversion is necessary for further processing and analysis within the microcontroller. Digital data allows easier manipulation, filtering, and transmission. The ESP32 processes both analog-converted data and digital data (from sensors like MAX30102) simultaneously, ensuring synchronization across multiple parameters for accurate real-time monitoring.

Stability and Placement: Proper placement of sensors on the human body plays a crucial role in obtaining accurate and consistent readings. Sensors must be positioned correctly to ensure effective signal detection. Secure connections between sensors and the microcontroller are also necessary to prevent data loss or signal fluctuations. Careful attention to stability reduces noise and improves reliability. Ensuring correct placement and stable connections helps maintain consistent performance of the system during continuous monitoring conditions.

IV. System Design

Biosensing Module: The biosensing module is responsible for collecting physiological signals from the human body using integrated sensors. It includes sensors such as MAX30102 for heart rate and SpO_2, ECG sensors for cardiac activity, EMG sensors for muscle signals, and a temperature sensor for body temperature. These sensors continuously detect and generate signals corresponding to different vital parameters. This module acts as the first stage of the system, ensuring accurate and real-time acquisition of biomedical data for further processing and analysis.

Display and Communication Module: This module provides real-time feedback to the user and enables remote monitoring. The processed data is displayed locally on an LCD or OLED screen, showing parameters like heart rate, SpO_2, ECG, EMG, and temperature. In addition to local display, the ESP32's built-in Wi-Fi transmits data to cloud platforms such as Thing Speak or MQTT-based systems. This allows users, caregivers, or healthcare providers to monitor health data remotely from anywhere, enhancing accessibility and usability of the system.

Microcontroller Processing Unit: The microcontroller processing unit uses the ESP32 to manage and process the data collected from the sensors. It reads both analog and digital signals, performs signal conditioning, filtering, and converts analog signals into digital form using its ADC. The ESP32 processes multiple inputs simultaneously in real time, ensuring synchronization across different parameters. It acts as the central controller of the system, coordinating data acquisition, processing, and communication efficiently while maintaining overall system performance and reliability.

Power Management Module: The power management module ensures that all components of the system receive stable and regulated power for proper operation. It supplies energy to sensors, the ESP32 microcontroller, and display units while maintaining efficiency and reliability. Proper power regulation helps prevent fluctuations that could affect sensor accuracy or system performance. This module is essential for continuous monitoring, ensuring that the system operates smoothly over extended periods without interruptions or failures.

V. SYSTEM ARCHITECTURE AND DESIGN

The system architecture is designed to enable efficient acquisition, processing, and transmission of multiple physiological signals in real time. It is structured into four main modules: the biosensing module, microcontroller processing unit, display and communication module, and power management module. The biosensing module collects vital parameters such as heart rate, SpO_2, ECG, EMG, and body temperature using integrated sensors. These signals are then passed to the ESP32 microcontroller, which acts as the central processing unit.

The ESP32 handles both analog and digital inputs, performing signal conditioning, filtering, and analog-to-digital conversion to ensure accurate data processing. Once processed, the data is displayed locally on an LCD or OLED screen for immediate user feedback. At the same time, the ESP32 uses its built-in Wi-Fi capability to transmit data to cloud platforms, enabling remote monitoring. The power management module ensures stable and continuous operation by supplying regulated power to all components.All modules work together in a coordinated manner to provide a compact, low-cost, and real-time health monitoring system suitable for non-clinical applications.

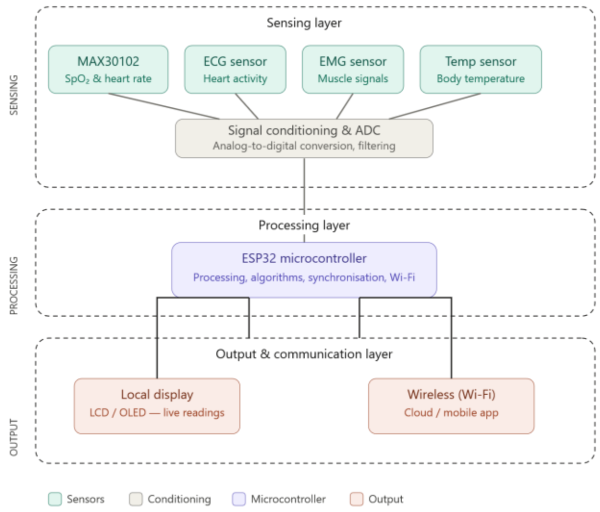


Fig.1. System Architecture

Most biomedical monitoring systems, despite their differences, tend to follow a similar underlying structure. At a high level, you can break it down into three stages: picking up the body's signals, making sense of them, and then presenting or transmitting the results. It all starts with data acquisition — sensors placed on or near the body that detect various physiological signals. Depending on what the system is designed to monitor, this might include PPG sensors for heart rate and blood oxygen levels, ECG or EMG electrodes, temperature sensors, or some combination of these.

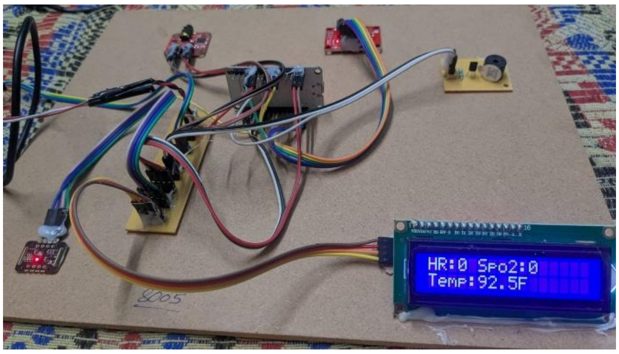
From there, the raw signals are handed off to a microcontroller — something like an Arduino, Raspberry Pi, or ESP32 — which handles the processing side of things. This typically involves converting analog signals to digital, applying filters to clean up noise, and running basic algorithms to extract meaningful readings from what can otherwise be pretty messy data.

Once processed, the data needs to go somewhere useful. In simpler setups, it's shown directly on a small screen — an LCD or OLED display attached to the device. More advanced systems send the data wirelessly over Wi-Fi or Bluetooth, feeding into cloud platforms or mobile apps that allow remote monitoring in real time.

One of the reasons this kind of architecture has taken off is that most of the components involved are inexpensive and widely available. That makes these systems realistic to build and deploy at scale. The catch, of course, is that how well a system actually performs comes down to the choices made during design — the right sensors, the right processing pipeline, and a layout that balances accuracy, power use, and dependability.

VI. Prototype Implementation

The developed system was tested under different conditions to evaluate its ability to acquire, process, and transmit physiological signals in real time. The prototype, built using the ESP32 along with MAX30102, ECG, EMG, and temperature sensors, was tested on a small group of volunteers. The system successfully measured multiple parameters, including heart rate, SpO_2, ECG signals, EMG activity, and body temperature. These values were displayed instantly on the local screen, while data was also transmitted to a cloud platform with minimal delay under stable network conditions. Heart rate and SpO_2 readings were generally stable, though slight variations were observed during movement. ECG and EMG signals were more sensitive to noise and required proper electrode placement for better accuracy. Basic filtering techniques helped improve signal clarity to an acceptable level. Temperature readings remained consistent throughout testing. Overall, the system demonstrated reliable performance for non-clinical use, confirming its effectiveness as a low-cost, real-time health monitoring solution.



The ESP32 was programmed to continuously acquire signals from all sensors, perform basic signal conditioning and filtering, and convert analog signals into digital form. The processed data was displayed in real time on a local LCD or OLED screen, providing immediate feedback to the user. Additionally, the built-in Wi-Fi capability of the ESP32 was used to transmit the data to cloud platforms, enabling remote monitoring. The prototype demonstrated the ability to handle multiple inputs simultaneously with minimal delay, confirming its effectiveness as a low-cost, real-time health monitoring system.

VII. RESULT

Testing showed that the system performs reliably for its intended purpose. Heart rate and SpO_2 readings were consistent under stable conditions, with only minor fluctuations during movement — expected behaviour for any wearable sensing setup. The ECG module captured cardiac activity clearly, producing recognisable waveform patterns, while the EMG sensors detected muscle activity with reasonable sensitivity. Temperature readings remained accurate and steady throughout. One of the more encouraging outcomes was the system's responsiveness — it reacted to signal changes quickly, with no noticeable lag, which is exactly what's needed in a real-time monitoring context. ECG and EMG signals did exhibit some noise, as is common with low-cost sensors, but basic filtering brought the signal quality to an acceptable level.

Overall, the system delivered dependable performance across all four parameters. It isn't designed for clinical-grade precision, and it doesn't claim to be — but for non-clinical applications like home health monitoring or educational use, it provides results that are genuinely useful. The combination of real-time responsiveness, multi-parameter coverage, and reasonable accuracy makes it a practical foundation for further development.

VIII. Future Scope

The Although the proposed system works well as a low-cost, multi-parameter health monitoring solution, there is still plenty of room for improvement and expansion. Future work can focus on making the system not just more capable technically, but also more practical and user-friendly in real-world use. One promising direction is the use of advanced signal processing and machine learning techniques. Instead of simply displaying readings, the system could be trained to recognize patterns and detect abnormalities automatically. For example, it could identify irregular heart rhythms or unusual trends in physiological signals and provide early warnings. This would make the system more useful for preventive healthcare rather than just basic monitoring. The system can also be expanded by adding more sensors. Parameters such as blood pressure, respiratory rate, or even glucose levels could be included to give a more complete picture of a person's health. This would be especially helpful for patients managing long-term conditions, where multiple factors need to be tracked continuously. Another important improvement would be in the physical design of the device. By making the hardware smaller and optimizing power usage, the system could be developed into a wearable form, such as a wristband or a small patch. This would allow users to monitor their health continuously without discomfort or inconvenience.

From a connectivity point of view, future versions should focus on improving data security and privacy. Since health data is sensitive, adding encryption and secure storage methods would be essential. At the same time, developing a simple mobile application could make the system easier to use by providing features like real-time alerts, data history, and basic health insights in a more user-friendly format. Finally, the system could be connected to larger healthcare networks, such as hospital systems or telemedicine platforms. This would allow doctors and healthcare providers to access patient data more easily, improving monitoring and decision-making. Overall, the future direction of this project is to evolve the current prototype into a smarter, more secure, and easy-to-use health monitoring system.

With further development, it has the potential to contribute meaningfully to accessible and everyday healthcare solutions.

IX. CONCLUSION

The proposed Biomedical Signal Instrumentation System demonstrates a practical approach to developing a compact, efficient, and cost-effective solution for monitoring multiple physiological parameters in real time. By integrating a set of commonly used biosensors with the ESP32 microcontroller, the system is able to acquire, process, and display biomedical signals in a reliable and synchronized manner. The use of both analog and digital sensing techniques, combined with basic signal conditioning and filtering, ensures that the captured data is sufficiently stable for continuous observation in non-clinical environments.

Another important aspect of this work is its focus on affordability and simplicity. The system is built using low-cost, readily available components, making it accessible for a wide range of users, including students, researchers, and individuals in resource-constrained settings. Its compact design and ease of operation also make it suitable for future extensions, such as wearable health monitoring devices or integration with advanced data analytics systems.

Experimental testing of the prototype indicates that the system performs consistently in acquiring and transmitting data, with acceptable accuracy for a non-clinical device and minimal communication delay. While it is not intended to replace certified medical equipment, it serves as a functional and scalable proof-of-concept for continuous health monitoring.

In conclusion, this project highlights the potential of combining embedded systems with IoT technologies to create accessible and practical healthcare solutions. It provides a foundation for further research and development in multi-parameter monitoring systems, contributing toward improved healthcare accessibility, early detection of health conditions, and more efficient patient care.

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