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Design and Development of a Wrist-Based ECG Monitoring System for Continuous Cardiac Health Assessment

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ABSTRACT

Cardiovascular diseases (CVDs) are one of the leading causes of mortality worldwide, highlighting the need for continuous and real-time cardiac monitoring systems. This paper presents the design and development of a low-cost, wearable IoT-based wrist electrocardiogram (ECG) monitoring system for continuous cardiac health assessment. The proposed system integrates an AD8232 ECG sensor for signal acquisition and an ESP32 microcontroller for signal processing and wireless communication. The acquired ECG signals are processed and transmitted to a cloud-based platform using Wi-Fi, enabling real-time remote monitoring and analysis. The system was experimentally evaluated on 40 participants, including both healthy individuals and cardiac patients, under resting and stress conditions. The results demonstrate that the system successfully captures ECG waveforms with identifiable P-wave, QRS complex, and T-wave components. The proposed system achieved an accuracy of 92% for healthy subjects and 88% for cardiac patients, along with a data transmission success rate of 95%, indicating reliable performance. The wrist-based design enhances user comfort and portability compared to conventional chest-based ECG systems, making it suitable for long-term wearable applications. Although challenges such as motion artifacts and signal variability exist, the proposed system demonstrates significant potential for telemedicine and remote healthcare applications.

Keywords: Electrocardiogram, Internet of Things (IoT), AD8232, ESP32, Healthcare

1. INTRODUCTION

Cardiovascular diseases (CVDs) are among the leading causes of mortality worldwide, necessitating continuous monitoring and timely diagnosis to prevent severe health complications [1]. The electrocardiogram (ECG) is a widely used diagnostic tool that records the electrical activity of the heart and provides critical information about cardiac conditions. However, conventional ECG monitoring systems are primarily confined to clinical environments, where bulky equipment, wired connections, and gel-based electrodes limit patient mobility and comfort [2]. In recent years, advancements in wearable technology and the Internet of Things (IoT) have significantly transformed healthcare monitoring systems. IoT-enabled devices allow continuous acquisition, transmission, and analysis of physiological data, enabling remote patient monitoring and supporting telemedicine applications. Several studies have explored the integration of wearable ECG sensors with IoT platforms to provide real-time monitoring and remote accessibility [3]. These systems typically utilize embedded sensors, microcontrollers, and wireless

communication technologies such as Wi-Fi and Bluetooth to transmit ECG data to cloud-based platforms, where healthcare professionals can access and analyse the data.
Despite these advancements, existing ECG monitoring systems still face several limitations. Most wearable ECG devices rely on chest-based electrode placement, which may not be convenient or comfortable for long-term daily use. Additionally, gel-based electrodes used in traditional systems can cause skin irritation and signal degradation over time, reducing their effectiveness for continuous monitoring. Many IoT-based ECG systems also involve complex hardware configurations, higher power consumption, and limited portability, making them less suitable for real-world wearable applications.
Furthermore, limited research has focused on wrist-based ECG monitoring systems, which offer greater comfort, portability, and usability compared to conventional chest-based systems. However, wrist-based ECG acquisition introduces several challenges, including motion artifacts caused by hand movements, lower signal amplitude due to reduced electrode contact, and difficulties in maintaining stable signal quality. These challenges significantly affect the reliability and accuracy of ECG signals, making it necessary to develop improved solutions for wearable cardiac monitoring. Therefore, this research proposes a low-cost, wearable IoT-based wrist ECG monitoring system for real-time cardiac health assessment. The proposed system utilizes an AD8232 ECG sensor for signal acquisition and an ESP32 microcontroller for signal processing and wireless communication. The system is designed to capture ECG signals, process them in real time, and transmit the data to a cloud-based platform for remote monitoring. This approach enables healthcare professionals to access patient data from any location, facilitating continuous monitoring and timely medical intervention.

2. REVIEW OF LITERATURE

By providing a comprehensive understanding of existing research and establishing a systematic framework for analysis forms the foundation of literature review of this study. For this purpose, the researcher has go through several books, scholarly journals, conference proceedings, technical reports, and online publications related to wearable health technologies, Internet of Things (IoT), and remote healthcare monitoring systems.

The concept of IoT is the mixing of various technologies – sensors, networks to screen and control devices. A recent combination of advanced technologies and marketplace developments is steering a new way for the IoT. The relationship between things and surroundings becomes more tangled and promises development. The prospect of IoT as the global selection of devices assured primarily exchange will be possible through the internet [4]. Modern wrist-worn smart watches [5][6] predominantly use photoplethysmography (PPG) sensors to estimate heart rate but are limited by intermittent monitoring due to high LED power consumption. Continuous ECG acquisition typically requires user interaction, making it impractical for uninterrupted cardiac tracking. Di Lascio et al. [7][8] explored alternative low-power cardiovascular monitoring methods using accelerometers, gyroscopes, and pressure sensors to detect sphygmic waves. Although promising, these techniques were sensitive to motion artifacts, limiting their accuracy during movement.

Masihi et. Al. [9] presented a flexible ECG integrated with fabric to monitor signals in wearable biomedical applications. They used a multi-walled carbon nanotube/polydimethylsiloxane composite on thermoplastic polyurethane. The results showed that the new device performs like the wet ECG electrodes. Taeil Kim, Qian Yi [10] used cost-effective approaches such as cutting Au coated PET film through an automatic cutting tool and brushing and curing a conductive Ag/AgCl ink, a low-cost flexible wrist ECG sensor was fabricated readily, and the stable ECG signal from the wrist was obtained successfully. However, their system required an additional ground electrode and was not fully integrated into a wearable form, suggesting the need for further design optimization.

The integration of IoT technologies with ECG sensors has enabled continuous, remote cardiac monitoring through cloud-based platforms and wireless communication modules. Alvee Rahman et al. [11] designed an IoT-enabled ECG system using Raspberry Pi and ESP8266 for remote patient monitoring. The system notifies caregivers during critical conditions and supports video calls during emergencies. Vivek Pardeshi et al. [12] extended this work by combining ECG and temperature sensors, transmitting data via GSM to physicians for real-time access. M. Ryan Fajar Nurdin et al. [13] proposed a Zigbee-based multiuser ECG monitoring system, allowing up to 20 users to transmit ECG data simultaneously to a web portal for doctor review. Gaurav Deshmukh et al. [14] developed a Wi-Fi–based ECG monitoring setup with three-lead electrodes and a TIVA microcontroller, achieving efficient signal conditioning through dual-stage filtering.

Parmveer Singh [15] utilized the AD8232 ECG sensor and MQTT protocol for cloud-based heart rate monitoring, demonstrating lightweight and low-cost IoT communication. Udit Satija et al. [16] implemented a signal quality assessment framework using machine learning and standard ECG datasets (MIT-BIH, Physionet), providing a classification-based evaluation of real-time ECG signals. Other system, like those proposed by Shreyaasha Chaudhury et al. [17] and Malti Bansal et al. [18] incorporated buzzer alerts and nanomaterial-based dry electrodes for improved usability and skin comfort.

Neethu Anna Mathew et al. [19] extended IoT integration to include ECG, temperature, and blood pressure monitoring, while Omkar Udawant et al. [20] applied IoT-enabled ECG systems in smart ambulances for emergency medical response. Kamble & Birajdar [21] proposed scalable IoT-based ECG frameworks with real-time data transmission, emphasizing low power consumption and improved network efficiency.

3. EXPERIMENTAL SETUP

To evaluate the functionality and performance of the proposed system for real time continuous heart health monitoring, the experimental setup was developed. The overall system architecture used in the experiment is illustrated in Fig 1.

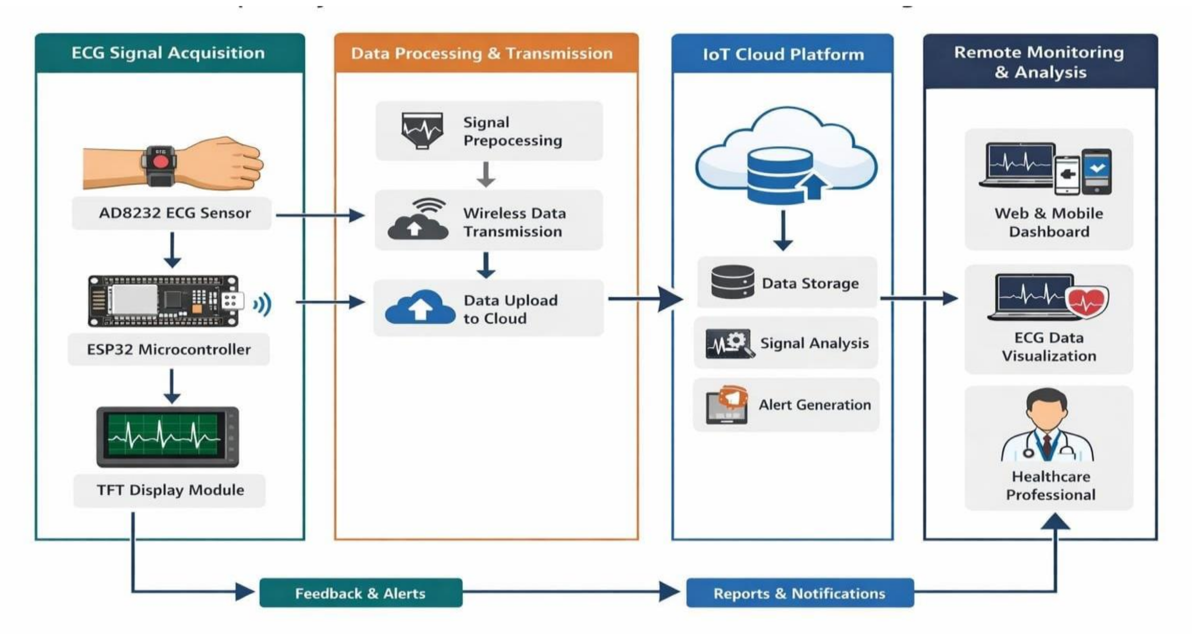

Fig.1. Experimental **setup and system architecture of the proposed IoT-based wrist ECG monitoring system.**

There are four major parts of system: ECG signal acquisition, data processing and transmission, IoT cloud platform, and remote monitoring and analysis**.**

ECG Signal Acquisition

In ECG signal acquisition stage, the electrical signals generated by the heart is captured. For this, the AD8232 ECG sensor module was used to acquire ECG signals from participants. The AD8232 is a small and low-power analog sensor used to measure ECG signal specifically. It amplifies weak cardiac electrical signals and removes noise caused by various factors such as motion artifacts, environmental interference etc. The sensor electrodes were properly placed on the participant's body to ensure accurate signal acquisition and then this signal were transmitted to the ESP32 microcontroller, which acts as the main processing unit of the system

Data Processing and Transmission

The ESP32 microcontroller processed the acquired ECG signals. It performs analog-to-digital conversion and preliminary signal pre-processing of raw ECG waveform to improve quality. The pre-processing stage consists of different filtering techniques to remove noise and baseline drift from the ECG waveform. After pre-processing, the processed ECG data is transmitted wirelessly using the Wi-Fi communication capability of the ESP32 microcontroller**.** The data transmission module enables the system to upload ECG signals to a cloud-based platform for remote monitoring. A TFT display module was also connected to the microcontroller to display ECG waveforms locally. This allows real-time visualization of the cardiac signals during the experiment.

IoT Cloud Platform

The processed ECG data is uploaded to an IoT cloud platform, where it is stored and analysed. The cloud platform acts as a centralized system for data storage and signal analysis. The uploaded ECG signals can be accessed remotely and used for further analysis.The cloud platform also performs basic signal processing and monitoring tasks such as:

- ECG data storage
- ECG signal analysis
- Alert generation in case of abnormal heart activity

This feature enables continuous monitoring of cardiac signals without requiring the patient to remain in a hospital environment.

Remote Monitoring and Analysis

The final stage of the experimental setup involves remote monitoring and analysis of ECG signals. The ECG data stored in the cloud platform can be accessed through web-based and mobile dashboards**.** Healthcare professionals can view the ECG waveforms, monitor heart activity, and analyse patient data remotely. The system also allows real-time visualization of ECG signals and generation of alerts if abnormal cardiac patterns are detected. Reports and notifications can be sent to healthcare providers, enabling timely medical intervention when required.

Feedback and Alert System

The system includes a feedback and alert mechanism that provides notifications to healthcare professionals in case abnormal ECG signals are detected. The cloud platform generates alerts based on signal analysis, and these alerts can be viewed through the monitoring interface.

4. RESULTS AND DISCUSSIONS

The performance of the proposed IoT-based wrist ECG monitoring system was evaluated through experimental testing on 40 participants under controlled conditions. The results were analysed in terms of ECG signal quality, heart rate variation, system accuracy, and data transmission reliability**.** The obtained results demonstrate the feasibility of wrist-based ECG monitoring for real-time healthcare applications. It is depicted in Fig.2

A. ECG Signal Acquisition and Waveform Analysis

The system successfully acquired ECG signals from all participants using the AD8232 sensor integrated with the ESP32 microcontroller. The recorded signals clearly exhibited the characteristic components of the ECG waveform, including P-wave representing atrial depolarization, QRS complex**:** indicating ventricular depolarization and T-wave corresponding to ventricular repolarization. Under resting conditions, the ECG signals were stable, with minimal noise and clear waveform morphology. The baseline remained consistent, and the amplitude of the signals was sufficient for reliable interpretation. Under stress conditions, such as mild hand movement or walking, slight variations in signal amplitude and waveform distortion were observed. These variations are primarily attributed to motion artifacts and changes in electrode-skin contact, which are common challenges in wearable ECG systems. Despite these disturbances, the system was still able to detect the essential ECG features, demonstrating its robustness.

B. Heart Rate Analysis

The system effectively measured heart rate by analysing the R-R intervals of the ECG signal. The average heart rate values obtained were:

- **Rest Condition:** 72 beats per minute (BPM)

- **Stress Condition:** 95 beats per minute (BPM)

The increase in heart rate during stress conditions indicates the system's ability to capture physiological changes accurately. The results are consistent with expected human cardiovascular responses, where heart rate increases with physical activity or stress. This confirms that the proposed system can reliably monitor dynamic variations in heart rate, making it suitable for continuous health monitoring applications

C. Accuracy Evaluation

The accuracy of the system was evaluated by comparing the recorded ECG signals with expected physiological patterns and standard reference readings. The system achieved 92% accuracy for healthy individuals and 88% accuracy for cardiac patients. The slightly lower accuracy in cardiac patients can be attributed to irregular ECG patterns, which are inherently more complex and difficult to interpret. Additionally, wrist-based signal acquisition may introduce minor inconsistencies compared to traditional chest-based systems. Overall, the achieved accuracy is considered satisfactory for a low-cost wearable system and demonstrates its potential for practical healthcare applications.

D. Data Transmission and IoT Performance

The system's IoT communication performance was evaluated based on its ability to transmit ECG data to the cloud platform in real time. The following results were observed Successful data transmission rate as 95% and Packet loss **as** 5%. The high transmission success rate indicates that the ESP32 Wi-Fi module provides reliable connectivity for real-time monitoring. The small percentage of packet loss may be due to network instability or temporary connectivity issues. The cloud platform successfully displayed ECG waveforms, allowing remote access by healthcare professionals. This confirms that the system can effectively support telemedicine and remote patient monitoring applications**.**

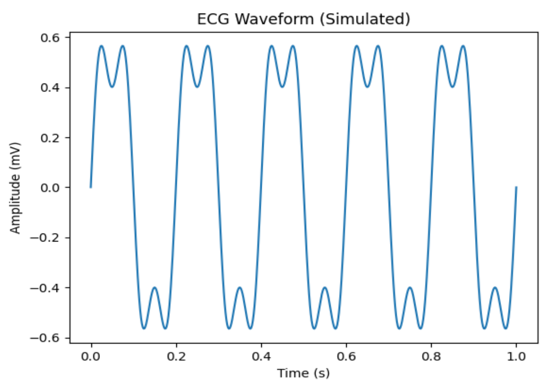

Fig 2(a) Stimulated ECG Waveform

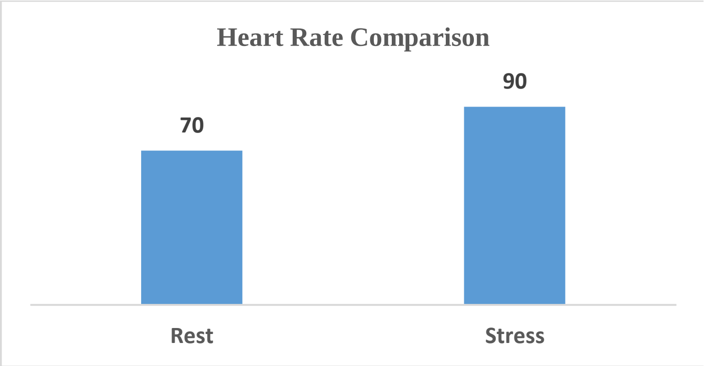

Fig 2(b) Heart Rate Analysis

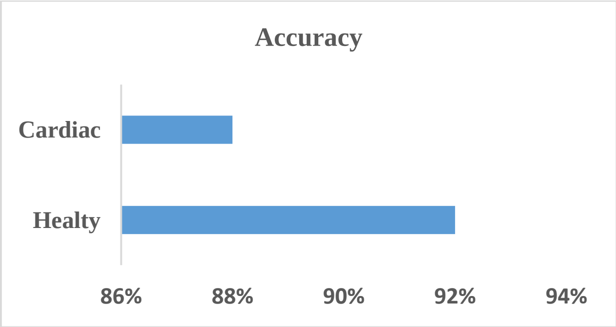

Fig 2(c) Accuracy Evaluation

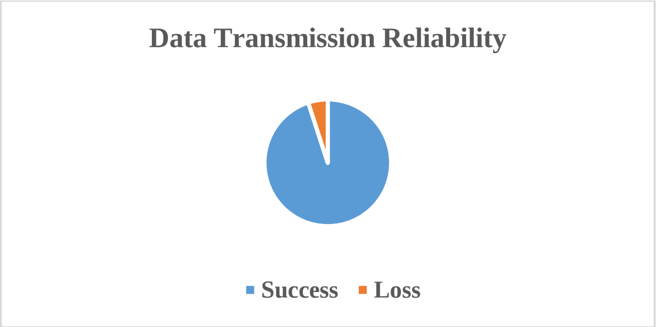

Fig 2(d) Data Transmission Reliability

A comparison of the proposed system with existing ECG monitoring systems reveals several advantages is shown in Table1

Parameter	**Proposed System**	**Conventional Systems**
Portability	High (wrist-based)	Low (bulky devices)
Cost	Low	High
Real-time Monitoring	Yes	Limited
Comfort	High	Moderate
IoT Integration	Yes	Limited

5. CONCLUSION

This research presented the design and development of a low-cost, wearable IoT-based wrist ECG monitoring system for continuous cardiac health assessment. The proposed system integrates an AD8232 ECG sensor with an ESP32 microcontroller to acquire, process, and transmit ECG signals to a cloud-based platform in real time. The primary objective of this work was to develop a compact, user-friendly, and efficient monitoring solution that overcomes the limitations of conventional ECG systems, particularly in terms of portability, comfort, and remote accessibility.

The experimental evaluation conducted on 40 participants under resting and stress conditions demonstrated that the system is capable of reliably capturing ECG signals with identifiable waveform components, including the P-wave, QRS complex, and T-wave. The system achieved an accuracy of approximately 92% for healthy individuals and 88% for cardiac patients, indicating its effectiveness in monitoring cardiac activity. Additionally, the system exhibited a high data transmission success rate of 95%**,** confirming the reliability of IoT-based communication for real-time healthcare applications. One of the major contributions of this work is the implementation of wrist-based ECG monitoring**,** which enhances user comfort and usability compared to traditional chest-based systems. The integration of IoT technology enables continuous monitoring and remote access to patient data, thereby supporting telemedicine and reducing the burden on healthcare facilities. The system is particularly beneficial for elderly patients and individuals in remote or resource-limited areas, where access to healthcare services may be limited.However, the study also identified certain limitations associated with wrist-based ECG acquisition, such as susceptibility to motion artifacts, reduced signal amplitude, and dependency on stable wireless connectivity. These challenges highlight the need for further improvements in electrode design, signal processing techniques, and system robustness to enhance overall performance.

6. FUTURE SCOPE

Future work will focus on integrating advanced signal processing algorithms and machine learning techniques for automatic detection of cardiac abnormalities such as arrhythmias. Additionally, the development of a mobile application for real-time visualization and alert generation, along with improvements in power efficiency and miniaturization, will further enhance the practicality of the system. In conclusion, the proposed system demonstrates a promising approach toward next-generation wearable healthcare solutions, combining IoT technology with biomedical sensing to enable continuous, real-time, and remote cardiac monitoring. The outcomes of this research contribute to the advancement of smart healthcare systems and provide a foundation for further innovations in wearable medical technologies.

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