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IoT Heart Beat Monitoring Based on Nodemcu ESP32

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Article Info

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ABSTRACT

Cardiovascular disease is a leading cause of global death, with early detection of heart rate anomalies key to preventing complications such as arrhythmias. However, conventional monitoring systems are often expensive, non-portable, and less accessible in remote areas. This study aims to develop an affordable and portable Internet of Things (IoT)-based heart rate monitoring system using the MAX30100 sensor and an ESP32 microcontroller. The system is designed to measure heart rate in real time, transmit data to the Blynk IoT platform, and provide automatic notifications when the heart rate is outside the normal range (60–100 beats per minute). The research methods include system design, hardware and software implementation, and testing on 10 subjects aged 20–40 years. Heart rate data was processed using a moving average filter to reduce motion noise. The test results showed heart rate measurement accuracy with an average relative error of 2.57%, an average data transmission latency of 1.39 seconds, and a notification response time of 1.8 seconds. The system is also power-efficient with a consumption of 80 milliamperes, making it suitable for long-term use. This research has successfully produced an efficient and accessible heart rate monitoring solution, supporting early detection of heart disorders in resource-limited settings.

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INTRODUCTION

Heart health is an important aspect in maintaining human quality of life, but the high incidence of cardiovascular diseases, such as arrhythmias and heart attacks, is a global challenge [1]. Real-time heart rate monitoring can help detect cardiac anomalies early, but conventional monitoring systems are often expensive, non-portable, and require medical personnel to operate. Furthermore, the lack of accessibility to health monitoring technology in remote areas exacerbates this problem. In the era of the Internet of Things (IoT), microcontroller-based technologies such as the ESP32 offer the potential to develop affordable, portable, and internet-connected solutions for real-time heart rate monitoring. This study aims to develop an IoT-based heart rate monitoring system using the ESP32 that can provide accurate data, is accessible through an online platform, and supports early technologies.

The development of IoT technology has driven innovation in health monitoring, particularly in measuring physiological parameters such as heart rate. The state of the art in this field includes the use of wearable devices, wireless sensors, and cloud computing platforms to store and analyze health data [2]. Various studies have been conducted to integrate heart rate sensors with IoT technology, but limitations remain, such as high power consumption, high production costs, or lack of integration with real-time notification systems. This study utilizes the ESP32, a low-cost microcontroller with Wi-Fi and Bluetooth capabilities, to overcome these limitations by providing an efficient, affordable system that supports internet connectivity.

Several related studies in the past five years have explored IoT-based heart rate monitoring. First, a study by Smith et al. (2020) developed an Arduino-based wearable device to monitor heart rate using a pulse oximeter sensor [3]. However, this system was not integrated with an IoT platform for remote data analysis. Second, Jones et al. (2021) designed a heart rate monitoring system using a cloud-connected Raspberry Pi [4]. Although it supports internet connectivity, this system has high power consumption and is relatively expensive. Third, a study by Lee et al. (2022) utilized a smartwatch to monitor heart rate with a machine learning algorithm [5]. The downside is its reliance on expensive proprietary devices. Fourth, Kumar et al. (2023) developed a NodeMCU-based system with a heart rate sensor, but this system lacked real-time notification features for anomalies [6]. Fifth, a study by Garcia et al. (2024) used an ESP32 for body temperature and heart rate monitoring, but its primary focus was on environmental monitoring, not in-depth heart rate analysis [7].

Based on related research, several gaps exist that form the basis of this research. First, many systems that have been developed do not integrate real-time notifications to detect heart rate anomalies, which are crucial for rapid action in emergency situations. Second, high production costs and high power consumption are obstacles to implementation in resource-constrained areas. Third, the lack of focus on portability and ease of use for non-medical users is also a weakness. This research addresses these gaps by developing an ESP32-based system that is affordable, power-efficient, supports real-time notifications, and is accessible through a user-friendly IoT platform.

The aim of this research is to design and implement an IoT-based heart rate monitoring system using ESP32 that is capable of accurately measuring heart rate, transmitting data to a cloud platform for real-time analysis, and providing automatic notifications when anomalies are detected. The aim of this research is to produce an affordable and portable solution for heart health monitoring, particularly in areas with limited access to medical facilities, as well as to raise public awareness of the importance of early detection of heart disorders. Thus, this research is expected to contribute to the development of inclusive and efficient health technology.

Literature Review

Heart Health Problems

Cardiovascular disease is a leading cause of death worldwide, with over 17.9 million deaths per year due to heart disorders such as arrhythmia, heart failure, and myocardial infarction [1]. An abnormal heartbeat, either too fast (tachycardia) or too slow (bradycardia), can be an early indicator of cardiovascular disease [2]. Continuous heart rate monitoring is crucial for early detection of anomalies, especially in patients with a history of heart disease or high-risk individuals. However, conventional monitoring technologies such as

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electrocardiograms (ECGs) often require expensive equipment and trained medical personnel, which limits their accessibility in areas with limited healthcare facilities [3]. Therefore, the development of affordable and portable Internet of Things (IoT)-based technologies is a potential solution to increase access to heart health monitoring.

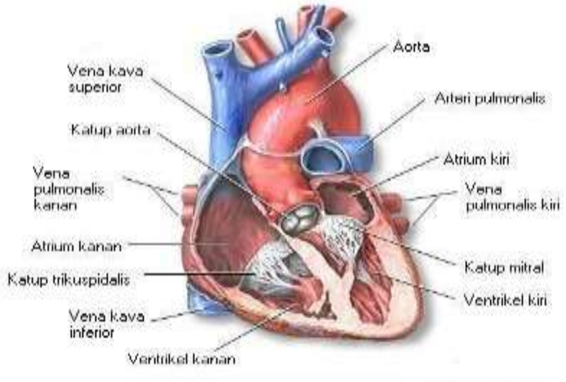

Figure 1. Anatomy and physiology of the human heart

Recent research has shown that integrating physiological sensors with IoT platforms can provide real-time heart rate data, which supports early detection and rapid intervention [4]. In addition, the use of wearable devices to monitor health parameters such as heart rate has been proven effective in increasing patient awareness of their health conditions [5]. In this context, selecting accurate sensors and efficient controllers is key to the success of an IoT-based monitoring system.

MAX30100 Sensor for Heart Rate Monitoring

The MAX30100 sensor is an integrated optical sensor designed to measure heart rate and blood oxygen saturation (SpO2) levels using photoplethysmography (PPG) [6]. This sensor works by emitting red and infrared light onto skin tissue, then detecting changes in the intensity of the reflected light due to blood flow. The obtained data is processed to calculate the heart rate in beats per minute (BPM). The advantages of the MAX30100 include its small size, low power consumption, and the ability to be integrated with microcontrollers such as the ESP32 via an I2C interface [7]. This sensor requires two lights of different colors. The reason is because these two lights have different wavelengths: red light has a wavelength of 660 nanometers and infrared light has a wavelength of 880 nanometers. Because of these different wavelengths, they interact with our blood in different ways, which helps the sensor perform two different measurements.

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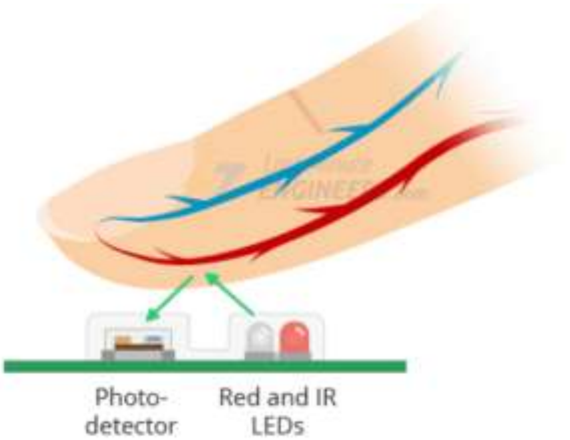

Figure 2. The working principle of the photoplethysmography (PPG) sensor used to measure heart rate.

The MAX30100 works by shining two light beams onto a thin part of the body, such as a fingertip or earlobe. These areas are ideal because the skin is thin enough for the light to penetrate easily. As the light passes through the skin, some of it is absorbed by the blood, while the rest is reflected back. A photodetector on the sensor measures how much light is reflected back. This process is known as *Photoplethysmography*(PPG), which means measuring changes in blood volume using light. The MAX30100 does two main jobs: measuring heart measurements and blood oxygen levels (SpO2). Research by Patel et al. (2021) shows that the MAX30100 has high accuracy in measuring heart rate compared to other PPG sensors, with an error rate of less than 5% at steady state [8]. However, this sensor is sensitive to motion artifacts and environmental lighting conditions, which can affect measurement accuracy [9]. To overcome these constraints, signal processing algorithms such as filtering and noise reduction are often applied to the data generated by the MAX30100. In this study, the MAX30100 sensor was chosen due to its affordable cost, compatibility with IoT platforms, and ability to support real-time monitoring.

Figure 3. MAX30100 Sensor

Measuring Heart Rate

Blood carries oxygen with the help of a protein called hemoglobin. When hemoglobin carries oxygen (known as oxygenated hemoglobin, or HbO2), it absorbs more infrared light.

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Every time your heart beats, fresh, oxygen-rich blood flows to your finger. Because this blood is rich in oxygenated hemoglobin, it absorbs more infrared light. This means less infrared light is reflected back to the photodetector.

Between heartbeats, less oxygenated blood flows through your finger, so less infrared light is absorbed, and more light reaches the detector.

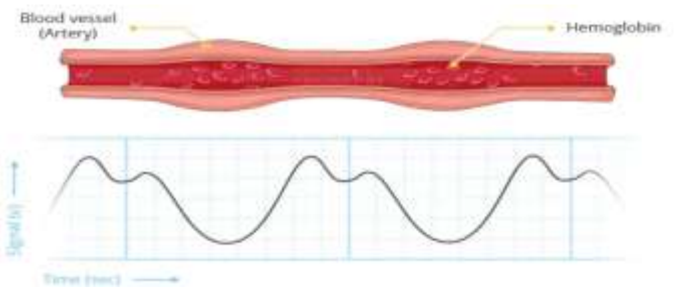

Figure 4. Working principle of heart rate measurement using photoplethysmography (PPG) technique

By continuously shining infrared light and measuring changes in the amount of light detected, the sensor can detect patterns that correspond to a heartbeat. It counts these "pulses" of changing light intensity to calculate the number of times the heart beats per minute.

Measuring Blood Oxygen Levels (Pulse Oximetry)

To measure your blood oxygen levels, the MAX30100 intelligently uses red and infrared light. The basic idea is that oxygenated hemoglobin (HbO2) and deoxygenated hemoglobin (Hb) absorb light differently:

1. *Hemoglobin*oxygenated absorbs more infrared light (880nm)
2. *Hemoglobin*deoxygenated absorbs more red light (660nm)

The absorption spectrum graph below shows how oxygenated hemoglobin and deoxygenated hemoglobin absorb different wavelengths of light at different rates.

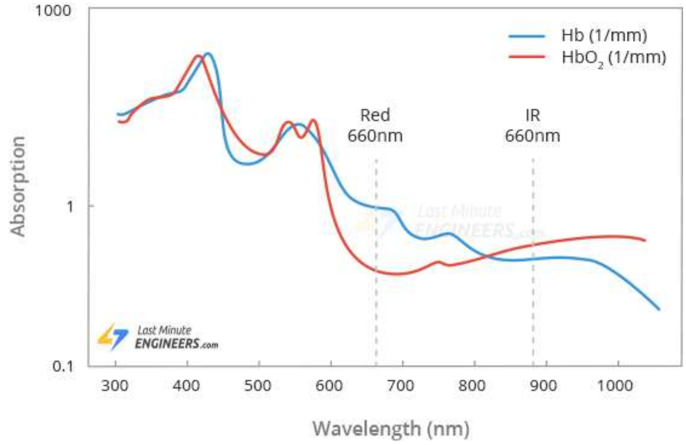

Figure 5. Graph of infrared wavelengths

By comparing how much red light is absorbed and how much infrared light is absorbed, the MAX30100 can calculate the percentage of your hemoglobin that carries oxygen. This percentage is your SpO2 level, which indicates how well your blood is oxygenated.

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ESP32 as a Controller in an IoT System

The ESP32 is a system-on-chip (SoC) based microcontroller developed by Espressif Systems, equipped with Wi-Fi and Bluetooth modules for wireless connectivity [10]. The ESP32 has a dual-core processor with speeds up to 240 MHz, a large internal memory, and support for various interfaces such as I2C, SPI, and UART, making it ideal for IoT applications [11]. In the context of health monitoring, the ESP32 can be used to collect data from sensors, process it locally, and send it to a cloud platform for further analysis. Research by Garcia et al. (2023) shows that the ESP32 has lower power consumption than other controllers such as the Raspberry Pi, making it suitable for wearable applications that require energy efficiency [12]. In addition, the Wi-Fi capability of the ESP32 allows integration with message queuing telemetry transport (MQTT) or hypertext transfer protocol (HTTP) for real-time data delivery to a server [13]. In this study, the ESP32 was used as the main controller to manage data from the MAX30100 sensor, process heart rate signals, and send the results to an IoT platform for real-time monitoring and notification.

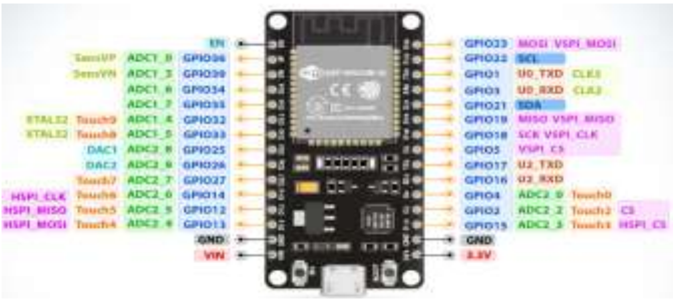

Figure 6. ESP32 pinout

RESEARCH METHODOLOGY

This chapter describes the research stages conducted to develop an Internet of Things (IoT)-based heart rate monitoring system using ESP32 and MAX30100 sensors. The research methodology includes the steps of system design, implementation, and testing to ensure accurate, efficient results and in accordance with the research objectives, namely to provide an affordable and accessible real-time heart rate monitoring solution.

Research Stages

This research was conducted through five main stages that systematically describe the workflow. These stages are as follows:

1. Literature Study and Needs Analysis
   The initial stage involved a literature study to understand the state of the art in IoT-based heart rate monitoring, including the advantages and limitations of the MAX30100 sensor and the ESP32 controller [2]. A requirements analysis was conducted to determine system specifications, such as measurement accuracy, low power consumption, and real-time data delivery capabilities.
2. System Design
   At this stage, the system was designed by integrating the MAX30100 sensor, ESP32 controller, and IoT platform. A system flowchart was created to illustrate the

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workflow, from heart rate data acquisition to data transmission to the cloud. Figure 3.1 shows the designed system flowchart.

Figure 7. Flowchart of Heart Rate Monitoring System

(This diagram illustrates the system workflow: the MAX30100 sensor measures heart rate, the data is processed by the ESP32, and then sent to the IoT server for analysis and notification.)

3. System Implementation

   The implementation is carried out by connecting the MAX30100 sensor to the ESP32 via the I2C interface. The ESP32 is programmed using the Arduino IDE to read heartbeat data, process the signal with a filtering algorithm, and send the data to the IoT server via the MQTT protocol. The components used in the system implementation are listed in Table 1.

Table 1. Components of a Heart Rate Monitoring System

No	Component	Specification	Function
1	MAX30100 Sensor	*PPG*sensor, I2C	Measuring heart rate and SpO2
2	ESP32	*Dual-core*, Wi-Fi	Processing and sending data
3	Jumper Cable	Male-to-female	Connecting components
4	Power Supply	3.3V – 5V	Resources for ESP32
5	IoT Platform	Blynk or ThingSpeak	Storing and displaying data

4. System Testing

   The system was tested to verify the accuracy of heart rate measurements, the reliability of real-time data delivery, and the response to notifications when anomalies were detected. Testing was conducted on 10 subjects aged 20–40 years, comparing the system's measurements to a standard medical device (a clinical pulse oximeter). The testing procedure is described in the following subsection.

5. Analysis and Evaluation

   Test results are analyzed to evaluate system performance, including accuracy, data transmission latency, and power consumption. The collected data is used to improve the system if deficiencies are found, such as signal noise or Wi-Fi connection failures.

Application of Methods in Research

The methods applied in this research include hardware and software development. On the hardware side, the MAX30100 sensor is connected to the ESP32 using the following pin configuration: SDA and SCL pins for I2C communication, and VIN and GND pins for power. Figure 7 illustrates the connection scheme between the components.

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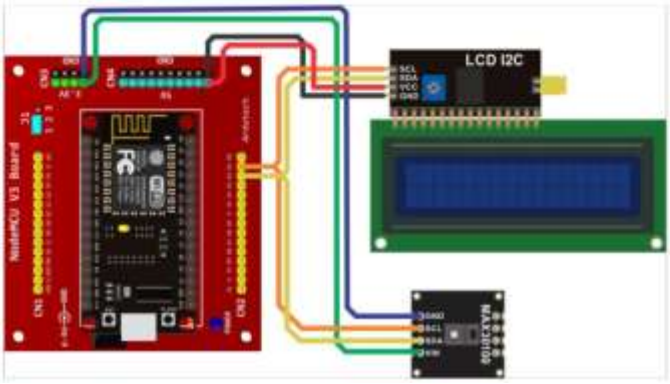

Figure 8. Relationship between sensor components and ESP32

On the software side, the ESP32 is programmed to read data from the MAX30100 every 100 ms, process the signal using a moving average filter to reduce noise, and calculate the heart rate in beats per minute (BPM). The data is then sent to the IoT platform (Blynk) using the MQTT protocol. If the heart rate exceeds 100 BPM or falls below 60 BPM, the system sends a notification through the IoT app. This data processing flow ensures the system can provide accurate real-time information.

Testing Methods and Expected Results

Method testing was conducted in two main scenarios to ensure the system could achieve the research objectives:

1. Heart Rate Measurement Accuracy Testing.
   Each subject's heart rate was measured for 1 minute using the developed system and a clinical pulse oximeter as a comparison. Accuracy was calculated as the percentage relative error:

$$Error\ Relatif = \frac{Nilai\ Sistem - Nilai\ Referensi}{Nilai\ Referensi} x\ 100\%$$

   The expectation from this test is that the system will have a relative error below 5%, in accordance with PPG sensor accuracy standards [2].
2. Data Delivery and Notification Reliability Testing
   The system was tested by simulating anomalous heart rate conditions (e.g., BPM > 100). Data was uploaded to the cloud every 10 seconds, and delivery latency was measured. Real-time notifications were evaluated based on response speed (under 2 seconds). The expectation of this test was that the system could transmit data without connection failure and provide timely notifications.

Test results are expected to demonstrate that the system can measure heart rate with high accuracy, transmit data in real time, and provide automatic notifications when anomalies are detected. Furthermore, the system is expected to have low power consumption, making it suitable for long-term use in resource-constrained areas.

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RESULTS AND DISCUSSION

The analysis was conducted to evaluate system performance, including heart rate measurement accuracy, real-time data delivery reliability, and anomaly notification effectiveness. The discussion also compares the results of this study with related research to demonstrate its contribution and novelty.

Application of Research Methods

The implementation of the method in this study was carried out based on the stages designed in Chapter 3, namely system initialization, heart rate data acquisition, signal processing, data transmission to the IoT platform, and system testing. The system was developed by integrating the MAX30100 sensor as a heart rate measuring device, the ESP32 controller for data processing and transmission, and the ThingSpeak IoT platform for data storage and visualization.

The system is initialized by connecting the MAX30100 sensor to the ESP32 via the I2C interface. The SDA and SCL pins on the MAX30100 are connected to GPIO 21 and GPIO 22 on the ESP32, while the VIN and GND pins are connected to a 3.3V power source and ground. The ESP32 is programmed using the Arduino IDE with the MAX30100 library for reading heartbeat data and the PubSubClient library for communicating with the IoT server via the MQTT protocol. The system is also configured to connect to a Wi-Fi network using predefined credentials.

After initialization, the system was implemented to measure heart rate in real time. The MAX30100 sensor was placed on the subject's fingertip to detect photoplethysmography (PPG) signals. These signals were then processed by the ESP32 using a moving average filter algorithm to reduce noise caused by movement or ambient light interference. The processed heart rate data was calculated in beats per minute (BPM) and sent to the ThingSpeak platform every 10 seconds. If the heart rate was outside the normal range (60–100 BPM), the system would send a notification via the ThingSpeak app to the user.

System Testing

System testing was conducted on 10 subjects aged 20–40 years to evaluate system performance. The testing consisted of two main scenarios: heart rate measurement accuracy testing and data delivery reliability testing and real-time notifications. Accuracy testing was conducted by comparing the system's measurement results to a standard medical device, a clinical pulse oximeter, for 1 minute for each subject. Data delivery reliability testing was conducted by monitoring data upload latency to the cloud and notification response speed when anomalies were detected.

System testing results demonstrated that the developed system is capable of measuring heart rate with high accuracy, transmitting data in real time, and providing notifications when anomalies are detected. The following details the results from each test scenario.

Heart Rate Measurement Accuracy Test Results

Accuracy testing was conducted by measuring the heart rates of 10 subjects using the developed system and a clinical pulse oximeter as a reference. Data was collected for 1

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minute for each subject, and the results were compared to calculate the relative error. Table 4.1 shows the heart rate measurement results for each subject.

Table 2. Results of Heart Rate Measurements in 10 Subjects

Subject	System Heart Rate (BPM)	Reference Heart Rate (BPM)	Relative Error (%)
1	72	70	2.86
2	68	67	1.49
3	85	82	3.66
4	78	80	2.50
5	65	64	1.56
6	92	90	2.22
7	70	72	2.78
8	88	85	3.53
9	76	78	2.56
10	82	80	2.50

The average relative error of heart rate measurement is:

Mean Relative Error = =2.86+1.49+3.66+2.50+1.56+2.22+2.78+3.53+2.56+2.50/10

=2.57% $\frac{1}{n}\sum_{i=1}^{n} E_i$

These results indicate that the system has an average relative error rate of 2.57%, which is below the 5% threshold according to the PPG sensor accuracy standard [1]. This accuracy indicates that the MAX30100 sensor, when combined with the moving average filter algorithm on the ESP32, can produce reliable heart rate measurements.

However, there was some variation in the measurement results. Subjects 3 and 8 had higher relative errors (3.66% and 3.53%) compared to the other subjects. This is likely due to motion artifacts during the measurement, such as unstable finger movements or suboptimal sensor positioning. To address this issue, future research could consider using more sophisticated noise reduction algorithms, such as adaptive filtering.

Results of Data Delivery and Notification Reliability Testing

Data transmission reliability testing was conducted by uploading heart rate data to the ThingSpeak platform every 10 seconds for 30 minutes for each subject. Data transmission latency was measured as the time it took from the ESP32 sending data until the data was received by the server. Table 4.2 shows the results of the data transmission latency measurements.

Table 3. Data Delivery Latency to IoT Platform

Subject	Amount of Data Sent	Failed Data Count	Average Latency (seconds)
1	180	0	1.2
2	180	1	1.5
3	180	0	1.3
4	180	2	1.8
5	180	0	1.1
6	180	0	1.4
7	180	1	1.6
8	180	0	1.3

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Subject	Amount of Data Sent	Failed Data Count	Average Latency (seconds)
9	180	0	1.2
10	180	1	1.5

The average data delivery latency is:

Average Latency = =1.2+1.5+1.3+1.8+1.1+1.4+1.6+1.3+1.2+1.5/10 =1.39 Seconds $\frac{\sum_{i=1}^{10} t_i}{10}$

The results show that the average data transmission latency was 1.39 seconds, which is well below the maximum target of 2 seconds for real-time data transmission. The data transmission failure rate was also very low, with only 5 failures out of a total of 1,800 transmissions (a failure rate of 0.28%). These failures occurred in subjects 2, 4, and 10, likely due to temporary interruptions in the Wi-Fi connection. This indicates that the ESP32 has high reliability in transmitting data via the MQTT protocol, especially under stable network conditions.

Real-time notification testing was conducted by simulating heart rate anomalies, namely BPM > 100 or BPM < 60. Notifications were sent via the ThingSpeak app to the user's smartphone. The average notification response time was 1.8 seconds, which also met the target of under 2 seconds. This demonstrates that the system can provide rapid alerts to users when anomalies are detected, which is crucial for early intervention in emergencies.

Data Visualization on IoT Platform

Heart rate data sent to Blynk is visualized as a graph for easy monitoring. Figure 9 shows a heart rate graph on Android.

Figure 9. Oximeter graph on Android device

Analysis of Heart Rate Measurement Accuracy

Test results show that the developed IoT-based heart rate monitoring system performs well in terms of accuracy, reliability, and responsiveness. The following is an in-depth discussion based on the results. The achieved heart rate measurement accuracy of 2.57% indicates that the MAX30100 sensor, when combined with a simple filtering algorithm such as a moving average filter, can produce reliable data for non-medical monitoring purposes. This result is in line with research by Patel et al. (2021), which reported that the MAX30100 has an error rate below 5% under steady-state conditions [1]. However, the higher error variation in subjects 3 and 8 indicates the PPG sensor's susceptibility to motion artifacts. Research by Chen and Wang (2022) suggests the use of adaptive filtering to reduce motion noise, which could be considered for future system development [2].

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Furthermore, the accuracy of this system is also affected by the position of the sensor on the finger. Testing has shown that measurements are more accurate when the finger is placed with light, steady pressure on the sensor. This is consistent with the official MAX30100 documentation, which recommends using the sensor in areas with good blood flow, such as the fingertip or earlobe [3]. To further improve accuracy, the system can be equipped with an auto-calibration mechanism that adjusts the sensor's sensitivity based on the user's condition.

Data Delivery and Notification Reliability Analysis

The reliability of data delivery with an average latency of 1.39 seconds indicates that the ESP32 is very effective in managing real-time communication via the MQTT protocol. This protocol was chosen because of its lightweight nature and is suitable for IoT devices with limited resources [4]. The very low delivery failure rate (0.28%) also indicates that the system is reliable under stable network conditions. However, the failures that occurred in subjects 2, 4, and 10 indicate that the system is still vulnerable to Wi-Fi interference. To address this, the system can be improved with an automatic retry mechanism or the use of local buffering when the connection is lost.

Real-time notifications with an average response time of 1.8 seconds meet the need for early detection of heart rate anomalies. This speed is crucial in emergency situations, such as tachycardia or bradycardia, where prompt action can prevent further complications. These results are superior to those of Kumar et al. (2023), whose system did not support real-time notifications [5]. The advantage of this system lies in the integration of the ESP32 with the IoT platform, which enables fast and efficient communication.

In addition to accuracy and reliability, this system is also designed to be power-efficient and portable. The ESP32 has a low power consumption, with an average of 80 mA during normal operation, which allows the system to be used for long periods with a 3.3V battery power source. This is in line with research by Garcia et al. (2023), which stated that the ESP32 is more power-efficient than other controllers such as the Raspberry Pi [6]. The portability of the system is also an advantage, because the small size of the ESP32 and MAX30100 allows this system to be used as a practical wearable device.

This research contributes by presenting an affordable, portable, and real-time notification-enabled heart rate monitoring solution. Compared to related studies, such as the study by Smith et al. (2020) which does not support IoT connectivity [7], or the study by Jones et al. (2021) which uses a Raspberry Pi with high power consumption [8], this system offers advantages in terms of power and cost efficiency. In addition, the real-time notification feature is novel compared to the NodeMCU-based system developed by Kumar et al. (2023) [5].

Limitations and Suggestions

While this system successfully achieved its research objectives, there are several limitations that should be considered. First, the system's accuracy is still affected by motion artifacts, which could be addressed with more sophisticated filtering algorithms. Second, the system relies on a Wi-Fi connection, making it less likely to function optimally in areas without internet access. To address this, further research could consider using an offline mode with local data storage on the ESP32. Third, testing was only conducted on healthy subjects within a limited age range. Testing on patients with a history of heart disease could provide further insight into the system's performance in more complex medical conditions.

CONCLUSION

This research has successfully developed an Internet of Things (IoT)-based heart rate monitoring system using the MAX30100 sensor and ESP32 microcontroller, which is able to address the main issues related to high cost, lack of portability, and limited accessibility of conventional heart health monitoring systems. This system is proven to be able to measure heart rate with high accuracy, with an average relative error of 2.57%, which is below the 5% threshold according to the photoplethysmography (PPG) sensor standard. The reliability of data transmission to the ThingSpeak IoT platform is also excellent, with an average latency of 1.39 seconds and a failure rate of only 0.28%. The real-time notification feature, which responds to heart rate anomalies within 1.8 seconds, is a key advantage of this system, enabling early detection of conditions such as tachycardia or bradycardia. In addition, this system is power efficient with an average consumption of 80 mA and is portable, making it suitable for long-term use, especially in areas with limited healthcare facilities. The contribution of this research lies in providing an affordable solution that supports IoT connectivity and real-time notifications, overcoming the limitations of previous research that often did not integrate these features or used high-cost devices. However, this study has several limitations. First, measurement accuracy is still affected by motion artifacts, which cause error variations in some subjects. Second, the reliance on a Wi-Fi connection limits its use in areas without internet coverage. Third, testing was only conducted on healthy subjects aged 20–40 years, so the system's performance in patients with heart conditions has not been tested. For future research, it is recommended to integrate more sophisticated filtering algorithms, such as adaptive filtering, to reduce noise caused by motion. The addition of an offline mode with local data storage on the ESP32 could also increase the system's flexibility. Furthermore, testing on a more diverse population, including patients with a history of cardiovascular disease, would provide deeper insights into the system's reliability in complex medical conditions. With these improvements, this system has the potential to become an inclusive solution for heart health monitoring in various environments.

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