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Original Article

IoT-Enabled Integrated Health Monitoring System: Real-Time Data Collection and Analysis for Improved Chronic Disease Management and Reducing Poverty

Abdifatah Farah Ali[1], Rusli Haji Abdullah[2], Abdikarim Abi Hassan[3], Husein Osman Abdullahi[4]

[1,4]*Faculty of Computing, SIMAD University, Mogadishu, Somalia.*
[2]*Department of Software Engineering and Information System, Universiti Putra Malaysia, Selangor, Malaysia.*
[3]*Faculty of Engineering, SIMAD University, Mogadishu, Somalia.*

[1]*Corresponding Author : fitaaxfarah@simad.edu.so*

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Abstract *- Healthcare monitoring systems are innovative technologies that facilitate real-time patient data tracking and analysis, enabling remote monitoring, personalized treatment, and improved diagnosis. These technologies increase productivity and efficiency and reduce costs, attracting global interest due to their potential benefits. Internet of Things (IoT) technology has transformed healthcare, shifting from in-person consultations to telemedicine. An IoT-based smart healthcare system that monitors a patient's vital health indicators and room environment in real-time is proposed in this study. Data is collected using five IoT sensors, including a heart rate sensor, a body temperature sensor, a room temperature sensor, a carbon monoxide sensor, and a carbon dioxide sensor. The error margin for each parameter is less than 5%. Patient situations are provided to medical professionals via a gateway, allowing for real-time processing and analysis. The system's efficiency proves it is suitable for monitoring healthcare and is an invaluable tool in modern healthcare environments by its effectiveness.*

Keywords *- Internet of Things, Telemedicine, Smart healthcare, Health monitoring, IoT sensors.*

1. Introduction

Health is a comprehensive condition of well-being that encompasses being physically, mentally, and socially healthy, and it is essential for achieving a higher quality of life. The global health issue has resulted in challenges due to several situations, including the lack of medical professionals and nurses during the most challenging moments [1].

Smart healthcare addresses the issues of limited healthcare resources and gaps between rural and urban areas by providing advanced diagnostic tools and real-time monitoring equipment, ultimately increasing patient care and overall healthcare quality. Smart healthcare enables patients to respond effectively in crucial situations [2]. It enhances healthcare providers' ability to expand their services beyond geographical boundaries and reduces treatment expenditures by facilitating remote check-up services.

To ensure that users receive health services, a robust smart healthcare system is necessary as smart cities grow. In addition to improving well-being, one of the main benefits is the reduction of healthcare costs through the utilization of prompt diagnoses. Kevin Ashton, in 1999, invented the Internet of Things (IoT), which is a network of connected devices that communicate and share data via the Internet, allowing for automation and increased efficiency in a variety of applications [3].

IoT is the result of advanced studies in Information and Communications Technology (ICT), and it can potentially improve the quality of life for urban residents. The development of cost-effective healthcare systems that can effectively manage and provide various medical services while minimizing overall costs is essential due to the accelerated global population growth and the increasing occurrence of chronic diseases [4]. According to Allen [5], the market for intelligent healthcare that utilizes the Internet of Things (IoT) is expected to be worth 158.1 billion dollars in 2022.

IoT has emerged as a transformative technology over the past decade, marking the beginning of a new era of innovation by connecting objects internally. Some IoT applications include intelligent health monitoring mechanisms [1, 6], smart parking [7], smart homes [8], smart cities [9], and agricultural fields [10]. IoT is widely used in healthcare management, offering tools for monitoring environmental and health conditions and connecting computers to the Internet via networks and sensors [11]. These interconnected components can be integrated into health monitoring devices, with sensors providing data to remote places such as Machine-to-Machine (M2M) systems, computers, handheld devices, smartphones, and people-to-people networks [12].

IoT is a simple, scalable, interoperable, and energy-efficient way to optimize care for a variety of health concerns by integrating modern systems that include versatile interfaces [13], assistant devices [14], and mental health management [15] to improve people's quality of life. IoT is expected to improve healthcare by reducing healthcare management costs, enabling individualized treatment, and enhancing patient outcomes.

The IoT allows doctors to remotely monitor patients, effectively schedule appointments, and improve home healthcare by reducing the number of doctor visits and unnecessary treatments, ultimately improving patient safety and reducing care costs [16]. The IoT enables remote health monitoring, streamlining hospital processes, and continuously monitoring the body and environment. This will aid in chronic disease management and rehabilitation progress and facilitate efficient data connections for virtual consultations in remote medical care [17]. The body temperature and heart rate are crucial indicators of human health, with a heart rate, or pulse rate, measuring the per-minute heartbeats, with standard ranges between 60-100 beats per minute for healthy individuals; in general, the resting heart rate of adult males is approximately 70 beats per minute, but the average resting heart rate of females is 75 beats per minute [18].

Several techniques for evaluating heart rate and body temperature have consistently demonstrated accuracy and convenience for consumers over a period of time [19]. To ensure patient comfort, healthcare should provide good room conditions, humidity, and CO2 levels [20]. Optimal humidity ranges from 30 to 65%. Studies focus on smart homes, not dedicated healthcare [21]. However, there are numerous fatal diseases in the medical sector, including heart disease [22], breast cancer [23], liver disorder [24], and diabetes [25]. The objective of the proposed IoT system is to continually monitor and assess the vital signs of all patient types and the surrounding environment of their rooms to provide optimal care and safety. The paper evaluates and proposes an IoT-based healthcare monitoring system that improves patient quality of life by connecting patients with healthcare providers using sensors to monitor pulse, body temperature, room humidity, CO, and CO2 levels, thereby reducing the need for a single hospital patient database.

The rest of this article follows this structure: Section 2 is a literature review of IoT health monitoring systems. Section 3 presents the major hardware component used in this study. Moreover, Section 4 addresses the system design methodology, whereas Section 5 summarizes the implementation details, followed by the analysis of the experimental results. Finally, Section 6 presents the conclusions with a discussion of future work.

2. Literature Review

Smart healthcare uses advanced diagnostic instruments and real-time vital signs to improve patient treatment and enhance healthcare quality [26]**.** It includes medical practices, pharmacies, home health services, long-term care facilities, medical equipment producers, insurance firms, and governments offering end-user services [27]. Acharya and Patil [28] developed an IoT-based healthcare monitoring system that tracks essential health parameters, including heartbeat, ECG, body temperature, and respiration, using IoT sensors for a pulse, temperature, blood pressure, and ECG, all integrated with a Raspberry Pi; however, these device collects data and sends it to the system, but it lacks data visualization interfaces for comprehensive analysis.

Al-Sheikh and Ameen [29] proposed a health monitoring system based on IoT used for smartphones that remotely monitor patients' vital signs, including body temperature, blood oxygen saturation, and electrocardiogram, and the data is sent to a cloud service known as Blynk for real-time monitoring, and Arduino is used for measurement and processing requirements. The findings are transmitted to a particular smartphone for monitoring by the healthcare professional. There is a need for enhancement as two microcontrollers are used: Arduino and Node-MCU. Banerjee and Roy [30] proposed a pulse rate detection system using plethysmography. It provides real-time monitoring that is more reliable than other invasive techniques, highlighting its potential for improving patient care.

Hamim et al. [31] developed a smart healthcare monitoring system within an IoT environment for patients and older adults, using an Android application that collects BT, HR, and GSR data from sensors and transfers it to a single Arduino Uno platform, enabling medical professionals to monitor patients' health and provide prescriptions. Gregoski et al. [32] developed a heart rate monitoring system based on a smartphone that uses a mobile light and camera to monitor the blood flow in the fingers and calculate the cardiac output, wirelessly transmitting pulses for heart rate measurement without manual contact. However, the design is not suitable for continuous heart monitoring.

Table 1 provides a summary of recent studies on IoT-based healthcare-monitoring systems. Kumar, et al. [33] proposed an adaptable IoT safety monitoring with a three-layered design consisting of control, device, and transport layers. The system measured body temperature using a DS18B20 sensor, while the pulse was measured using a pulse sensor. The transport of data from Arduino to the cloud was accomplished by utilizing an Ethernet shield and a Wi-Fi module. The framework layer obtained server information;

however, the Arduino Uno may not adequately handle multiple sensors simultaneously.

Raj [34] developed an innovative IoT healthcare monitoring system that effectively manages large amounts of data and it has three different stages for managing the data such as data collection, analysis, and decision-making. This system handles offline processing and real-time data collecting through Apache Kafka and Hadoop.

The proposed system achieves 97% higher accuracy in data processing and information extraction compared to standard neural network models using clustering and backpropagation; however, the study does not compare the effectiveness of time management. Kaur, et al. [35] proposed a healthcare system that improves patient-healthcare professional interactions by utilizing an IoT and Random Forest Classifier. The study used eight datasets on various diseases and five machine-learning approaches. The Random Forest technique achieved a maximum accuracy of 97.26% on the dermatology dataset, with Random Forest demonstrating accuracy and strong performance across all datasets.

Our previous study developed an IoT healthcare system to monitor elderly patients' vital signs, including temperature, blood pressure, and sleep patterns, using specialized equipment for continuous real-time data monitoring and sending email notifications to medical professionals when a concern arises.

This study offers a potential road map for future research by providing useful insights into the potential applications and limitations of the IoT in the healthcare industry. Desai and Toravi [36] developed a wireless sensor network that monitors a patient's heartbeat using Spartan3 for parallel data processing and an FPGA architecture. However, the findings are displayed on a Liquid Crystal Display (LCD), and its components aren't integrated into a single unit.

Table 1. Existing literature in IoT healthcare monitoring system

Author	Objectives	Methodology	Strength	Limitations
Swaroop et al. [37]	Developed an IoT-based real-time system to monitor patient health and potentially save lives.	The developed system detects crucial parameters and sends them to the ESP32 for processing and cloud transmission over Wi-Fi.	A mobile application has been created for doctors to monitor patients' health and inform them if unexpected readings occur.	The accuracy of the system is dependent on the sensors.
Gupta, et al. [38]	The system uses IoT technologies to monitor and evaluate adult health in real-time from many patients.	The MCU has a keyboard, an LCD, sensors, menus and a keypad for easy access. The ESP8266 collects data and sends it to the cloud.	The device is user-friendly, efficient, and portable, alerting doctors and patients in abnormal situations.	The system employs two microcontrollers for data processing and transfer, but it is not recommended for long-range Wi-Fi applications.
Alamsyah, et al. [39]	Developed IoT-based systems that allow doctors to monitor patients' vital signs, facilitating diagnosis.	The system uses Raspberry Pi processes and accesses the internet via Wi-Fi.	Doctors can access patient data on Android mobile devices.	This system utilizes Wi-Fi, which is not recommended for long-range applications.
Wu, et al. [40]	Developed a wearable sensor that can assess physiological signs.	Three devices are used for transmission parameters: a Raspberry Pi 3, a smartphone, and a Bluetooth Low Energy (BLE) module.	The proposed system uses rigid-flex technology to ensure data encryption while measuring ECG, HR, and BT.	The primary limitations are range and bandwidth.
Souri, et al. [41]	An IoT-based system for monitoring student health was developed.	Data identification, collection, and pre-processing are used in the methodology.	Uses innovative medical technologies	Limited emergency services and lower response time.
Kaur, et al. [35]	Developed IoT and AI technologies to improve the interaction between medical professionals and patients.	The proposed system was evaluated using eight datasets.	The key contribution is to provide an automatic recommendation feature.	Area under the curve and accuracy are the only metrics that facilitate performance evaluations.

Hashim, et al. [42]	Developed an IoT healthcare monitoring system with multiple sensors and smart security.	The Arduino is connected to several sensors, an LCD displays the data, and the Wi-Fi module transmits data to the cloud.	SMS messages are transmitted to health professionals by sensors, which are secure and wearable devices.	The prototype's size needs to be improved and reduced.
Hussein and Osman [43]	Develop a system for monitoring and managing air quality in Somalia using IoT technology.	Presents an IoT-based system integrating air quality sensors with a cloud platform for real-time monitoring and data analysis.	Provides a practical solution tailored to Somalia's context. Uses real-time data for improved monitoring and response.	There is limited discussion on scalability. Potential challenges in data accuracy and sensor maintenance in the local environment.

3. Hardware Components

The proposed system utilizes several essential hardware components to monitor and manage patient health. The following are the components that are essential to the system's development:

3.1. ESP32 Microcontroller Unit (MCU) Module

The ESP32 Module is an IoT learning tool providing a complete Linux system on a compact, cost-effective platform. Device sensors and actuators are connected through GPIO pins, which is crucial for integrating IoT and healthcare technologies. At the same time, the ESP32's remarkable flexibility is enhanced by features such as integrated antenna switches, RF-balun, control amplification, low-noise amplifier, filters, and power management modules. The ESP32 reduces interface overhead for the primary application processor by functioning as either a slave to a host MCU or an independent system, and it may communicate with other Bluetooth and Wi-Fi devices via its SPI/SDIO or I2C/UART interfaces. The ESP32 Microcontroller Unit is shown in Figure 1.

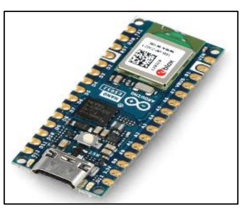

Fig. 1 ESP32 Microcontroller Unit (MCU) module

3.2. Heartbeat Sensor Module

The heartbeat sensor uses plethysmography, which detects differences in blood volume in an organ by measuring variations in light intensity passing through it. Blood volume changes because of heartbeats, which has an impact on how much light the blood can collect. The sensor can identify the timing of each pulse by monitoring the changes in light intensity that occur with each pulse. It is essential to have accurate pulse timing to monitor heart rate and ensure accurate heart activity tracking. Furthermore, the sensor's signal pulses coordinate with heartbeats, reflecting fluctuations in blood volume, which are directly influenced by the heart rate. This sensor makes it possible to monitor the performance of the heart continuously and consistently, which collects the data that is required for determining the heart's overall health. The Heartbeat Sensor Module is shown in Figure 2.

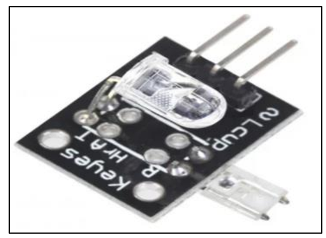

Fig. 2 Heartbeat sensor module

3.3. LM35 Body Temperature Sensor

The LM35 Body Temperature Sensor is a precision integrated-circuit temperature monitoring device with an output voltage linearly proportional to the Celsius temperature. Unlike other linear temperature sensors whose outputs are based on the Kelvin scale, the LM35 provides a user interface measurement because its Celsius scaling eliminates any need to subtract a nearly constant voltage from the display.

The sensor provides an accurate and linear temperature reading in medical and scientific applications. The LM35 focuses on high accuracy and can be easily used. It can measure temperatures from -55°C to 150°C; thus, the device will support locations in a wide temperature range. Figure 3 shows the LM35 Body Temperature Sensor.

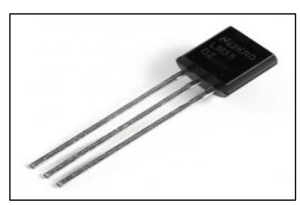

Fig. 3 LM35 body temperature sensor

3.4. DHT11 Environmental Room Sensor

The DHT11 Environmental Sensor measures room temperature and humidity. It features an 8-bit microcontroller that processes temperature and humidity information in series with a dedicated temperature measurement NTC. The sensor is factory-calibrated and, hence, easy to connect with other microcontrollers. Figure 4 shows the DHT11 Environment Sensor.

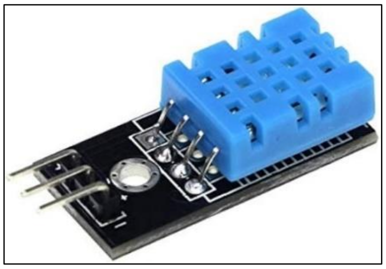

Fig. 4 DHT11 environmental room sensor

3.5. MQ-9 CO Detector Module

The MQ-9 sensor is designed to detect LPG, CO, and CH4 components present in the environment. It is highly sensitive and can provide rapid and precise measurements due to its fast response time. The measurements given are very fast in response. Adjusting the potentiometer is feasible, allowing for exact calibration based on specific detection requirements. The MQ-9 CO Detector Module is shown in Figure 5.

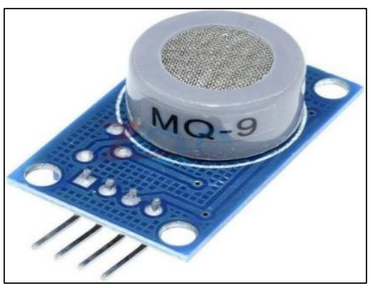

Fig. 5 MQ-9 CO detector module

3.6. MQ-135 CO2 Gas Sensor

The MQ-135 gas sensor detects and measures gases such as NH3, nicotine, benzene, smoke, and carbon dioxide in air quality management systems. The digital output of the MQ 135 sensor module is an independent device that helps identify gases without using a microcontroller. The analog pins determine the gases in PPM, and the sensor is compatible with most modern microcontrollers since it works on 5. The MQ-135 gas sensor is shown in Figure 6.

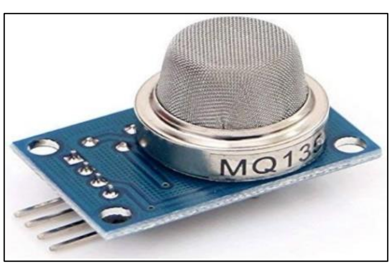

Fig. 6 MQ-135 gas sensor

4. Research Methodology

4.1. System Architecture

This section explains the proposed system, which monitors patients and their room environment. The system consists of five architectural layers: (1) Data Collection Layer, (2) Processing Layer, (3) Web Server Layer, (4) User Interface Layer, and (5) Medical Staff Layer. The data collection layer's sensors are wired and collect biological signals from the patient's body and surrounding environment.

After that, an ESP32 processing layer sensor processes the data before sending it to a communication layer web server. The web user interface interprets and presents the collected data, offering a real-time view of the patient status and ongoing processes.

The system uses the Hypertext Transfer Protocol (HTTP) to facilitate the connection between the Wi-Fi module and the web server. The user interface updates every 15 seconds, allowing for real-time tracking of both patients and their room environment. Figure 7 shows the overall architecture of the system.

All the sensors collect data on the patient and the room environment and are connected to the ESP32 processing unit, which serves as the system's central component. The ESP32 collects temperature, heart rate, and gas sensor data and sends it wirelessly to IoT platforms. This board is powered by an Xtensa dual-core 32-bit LX6 CPU and uses its integrated Wi-Fi to process and deliver data. The data can be accessible from any device that supports a network and can be displayed on a system that requires a password.

4.2. System Implementations

The system is implemented from a collection of hardware components assembled during the implementation phase, with the corresponding circuit diagram displayed in Figure 8. The ESP32 pins are used to physically connect each sensor to the board and act as the processing unit because of its built-in Wi-Fi capabilities. Each sensor's Vcc and GND pins are linked to the equivalent pins on the ESP32 designated for Vcc and GND. The signal pin of the heart rate monitor is connected to the ESP32's D26 pin.

The data port of the LM35 temperature sensor is connected to the D35 pin of the ESP32 microcontroller. The data pin of the DHT11 sensor is connected to the D14 pin of the ESP32 in the context of room condition monitoring, with the specific purpose of measuring room humidity.

The MQ-9 and MQ-135 gas sensors' digital output pins are attached to the ESP32's D27 and D34 pins to monitor dangerous gases in the room. The body temperature sensor (LM35) is connected, and the web server displays the data. Figure 9 shows the overall system implementation.

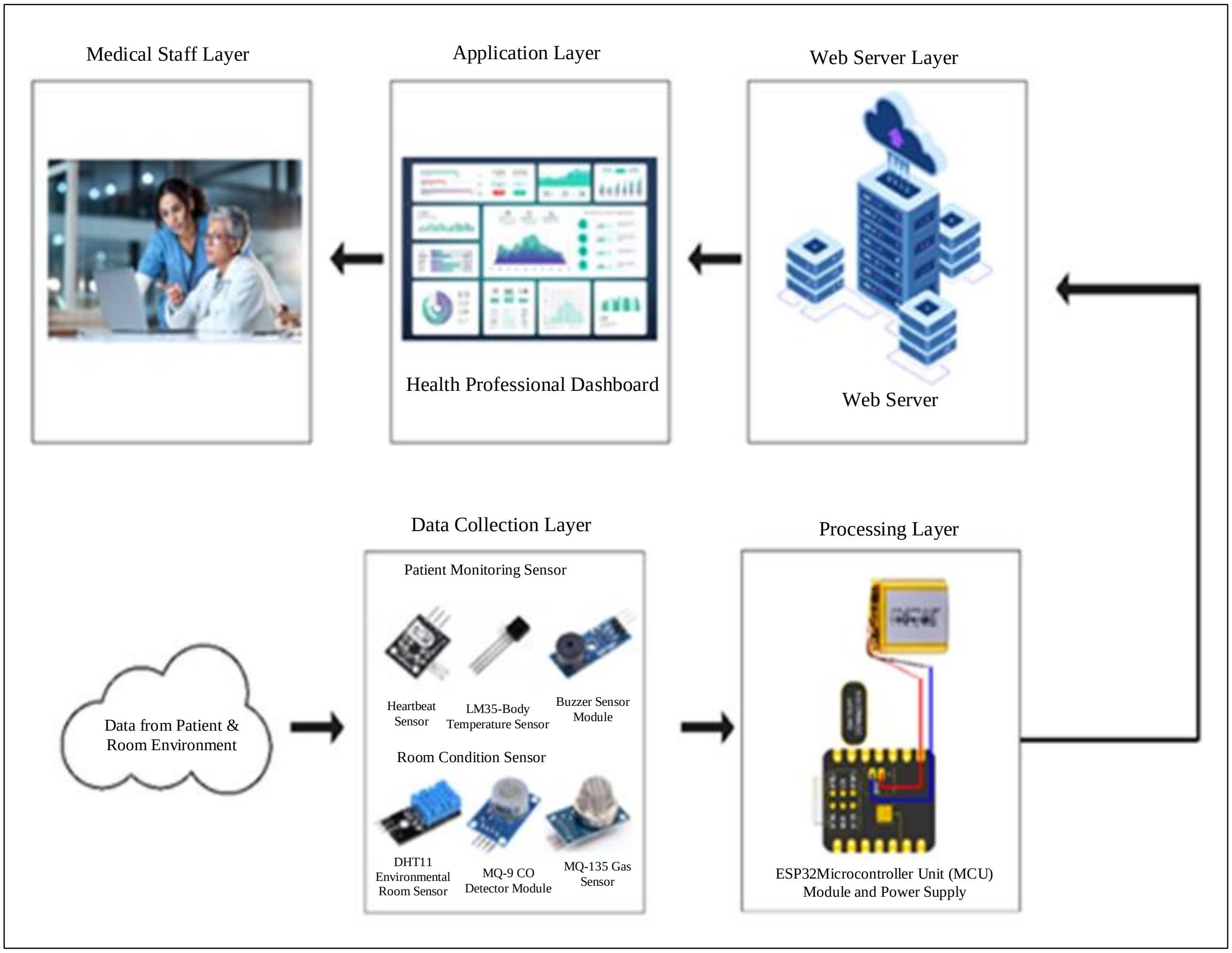

Fig. 7 System architecture

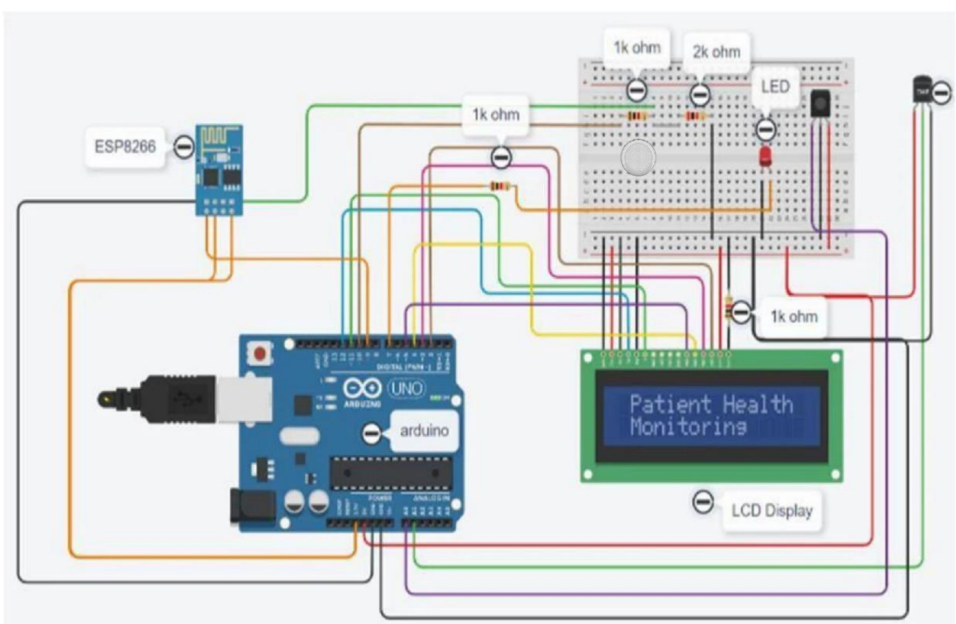

Fig. 8 System architecture using TinkerCad

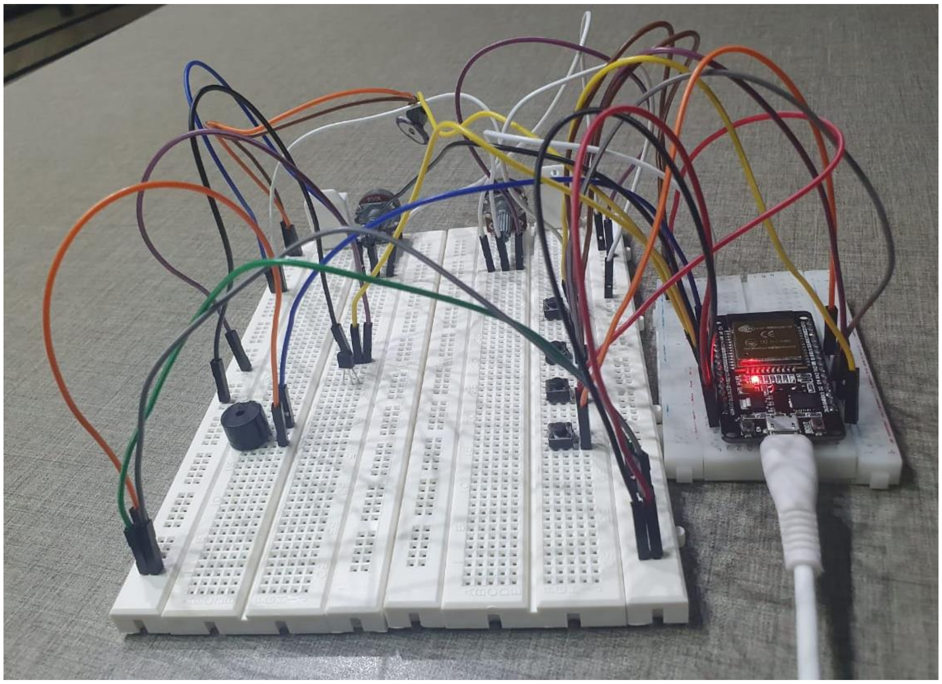

Fig. 9 System implementation

5. Results and Discussions

This section presents and discusses the experimental results obtained with the developed IoT system for health monitoring based on the system's accuracy and reliability compared to traditional analog measurements. Measurement data includes heart rate, body temperature, and environmental room humidity measured through specific sensors designed for precision and reliability.

5.1. Heartbeat Monitoring

Heartbeat data were obtained from the pulse sensor that measured beats per minute by detecting changes in the blood volume of the finger. The sensor works by providing a continuous cardiovascular monitoring feature, which is critical to detecting arrhythmia's response to stress and generally for assessing the health of a patient's heart.

This would be useful in monitoring a patient's activities during exercise or recovery from cardiac procedures, data that may be used in developing personalized treatment plans. These sensors will enable better patient monitoring in hospitals and with doctors through the real-time tracking of heartbeats, better diagnosis with consistent data, tailored treatment plans, and increased patient safety by early detection of potential problems, promoting timely interventions.

Therefore, automated data collection improves efficiency, reducing manual monitoring and freeing health professionals for more critical tasks. Table 2 compares the actual and observed data, with an average error percentage of around 2.75%. For example, Subject S1 had an actual rate of 68 bpm and a similar observed rate of 69 bpm.

Table 2. Heart rate data collected from an analog machine (actual) and a developed system (observed)

Subject	Actual Data (bpm)	Observed Data (bpm)	Error (%)
S1	68	69	1.47
S2	71	74	4.23
S3	75	78	4.00
S4	76	74	2.63
S5	72	71	1.39
S6	81	84	3.70
S7	70	72	2.86
S8	77	80	3.90
S9	79	81	2.53
S10	74	75	1.35

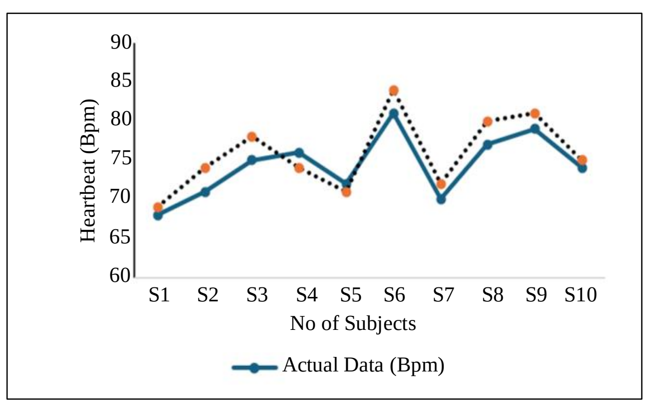

Fig. 10 The actual and observed values for heart rate data

5.2. Body Temperature Monitoring

The proposed system uses a temperature sensor to measure body heat in degrees Fahrenheit (°F), which helps continuously monitor the trend of body temperature for fever, hypothermia, or infections. This will enable health professionals to follow the temperature in real-time for the diseases of infection or postoperatively to monitor recovery. It also helps in assessing the effectiveness of treatments. These sensors offer several benefits to hospitals or doctors by enhancing patient monitoring through the detection of prompt temperature change and enhancing diagnostic accuracy by providing correct and accurate treatment.

The automated data helps to improve efficiency, reducing the manual monitoring effort and the workload of healthcare staff. Table 3 displays the high accuracy with an average percentage error of around 0.46%. For instance, Subject S1 showed the actual temperature value to be 97.20°F and an observed temperature of 97.60°F, in which the error was 0.41%. These comparisons are shown in Figure 11, which confirms the sensor's reliability in the clinical environment.

Table 3. Body temperature data collected from an analog machine and a developed system

Subject	Actual Data (°F)	Observed Data (°F)	Error (%)
S1	97.20	97.60	0.41
S2	98.30	97.80	0.51
S3	98.00	98.40	0.41
S4	97.00	97.40	0.41
S5	97.60	97.20	0.41
S6	98.10	97.30	0.82
S7	97.40	97.90	0.51
S8	98.20	97.50	0.71
S9	97.80	98.20	0.41
S10	98.00	97.60	0.41

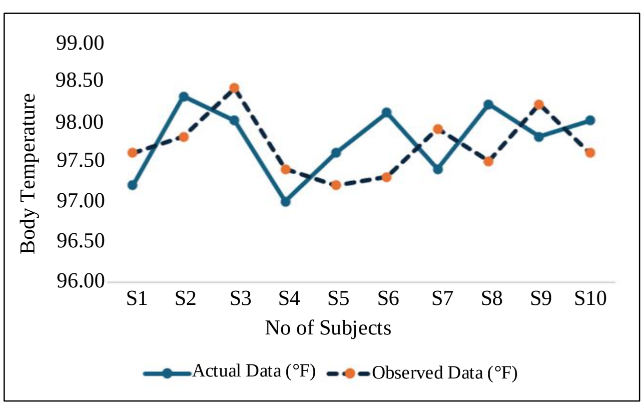

Fig. 11 The actual and observed values for body temperature

5.3. Environmental Room Humidity Monitoring

The proposed system uses a humidity sensor to measure the moisture level in the air, which is essential for maintaining optimal conditions in healthcare environments. It helps avoid respiratory issues and supports patients with respiratory diseases or weakened immune systems. The humidity sensor offers several benefits for hospitals and doctors, including improved air quality control, which helps prevent the spread of airborne pathogens and reduces the chances of infection. It also enhances the patient's care by making them feel comfortable, leading to faster recovery and reducing complications.

The automated monitoring system can easily adjust the facilities to maintain optimal conditions, increasing overall efficiency. The data is available on the web server, including readings from MQ-9 and MQ-135 gas sensors. Table 4 compares actual and observed data; the average percentage error is approximately 1.92%. For instance, the first experiment of actual humidity is 64%, and the observed humidity is 62%, resulting in a 3.13% error. Figure 12 shows the actual and observed falls, mainly within the limited region that this sensor has ensured is safe and comfortable for patients.

Table 4. Environmental room humidity data collected from an analog machine and a developed system

Experiment	Actual Data (%)	Observed Data (%)	Error (%)
1	64	62	3.13
2	67	68	1.49
3	64	63	1.56
4	69	71	2.9
5	65	63	3.08
6	62	61	1.61
7	66	65	1.52
8	71	70	1.41
9	63	62	1.59
10	68	67	1.47

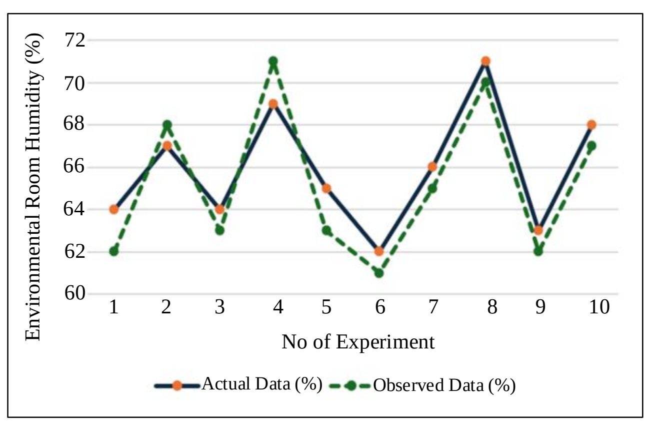

Fig. 12 The actual and observed values for environmental room humidity

6. Conclusion and Future Work

The proposed IoT-based healthcare monitoring system has the potential to significantly improve the quality of healthcare by continuously monitoring heartbeat, body temperature, and other environmental parameters like room humidity in real time. This study utilized five IoT sensors, including a heart rate sensor, a body temperature sensor, a room temperature sensor, a carbon monoxide sensor, and a carbon dioxide sensor.

For instance, the module for heartbeat monitoring reached an average error of 2.75%, body temperature monitoring showed an average of 0.46% error, and environmental room humidity monitoring had a low error margin of 1.92%. The results prove that this system can provide accurate, consistent data. This is critical in ensuring that patients are monitored effectively, hence timely medical interventions. Furthermore, the significant advantages of automated data collection and real-time access in this system include decreasing the manual workload of healthcare professionals and enhancing the diagnostic accuracy for customized treatment planning.

Therefore, the one-stop platform integrating sensors and IoT technology will bring improvement in efficiency and facilitate better patient outcomes, more specifically, management of chronic conditions and prevention of complications. Future work may include advanced algorithms for predictive analysis that are able to analyze data better by adding a comprehensive user interface with data visualization in real-time and alerts for better usability and the interventional process of health professionals, thus improving health outcomes and efficient delivery of healthcare. Also, the sensor devices should be further expanded to incorporate the measurement of oxygen saturation and air quality parameters. An added functionality in this respect is the user interface with data visualization in real-time and alerts for better usability and the interventional process of health professionals and health service takers/patients, thus improving health outcomes and efficient healthcare delivery.

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