Advances in Consumer Research
https://acr-journal.com/
Volume-2 | Issue-6 | Dec: 2025

Original Researcher Article

IoT-Based Space Suit Health Monitoring System Using AI for Real-Time Astronaut Safety.

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ABSTRACT

Astronauts work in extremely harsh conditions during space missions, and ongoing health monitoring is crucial to both mission success and survival. Conventional spacesuits lack sophisticated biomedical monitoring and only offer rudimentary life-support feedback. To measure, process, and communicate an astronaut's physiological and environmental characteristics in real time, this project suggests an Internet of Things-based Space Suit Health Monitoring System. A low-power microcontroller unit (MCU), such as the ESP32 or Arduino, interfaces with a number of embedded sensors, including heart rate, body temperature, oxygen saturation (SpO_2), and suit pressure sensors. For ongoing monitoring, data from these sensors is analyzed and wirelessly sent to a ground station or mission control using Wi-Fi or radio frequency communication. An IoT dashboard or monitoring software visualizes the collected data, allowing for quick action in the event of anomalous conditions.

This system prioritizes dependability in harsh environments, low power consumption, and compactness. By offering real-time health information and predictive alerts, it improves astronaut safety by assisting in the prevention of dangerous circumstances like hypoxia, hyperthermia, or suit malfunction. The suggested concept shows how IoT technologies and embedded electronics can greatly improve human spaceflight health monitoring.

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1. INTRODUCTION:

Space exploration has always been one of humanity's most remarkable achievements, yet it poses extreme challenges to human life. Astronauts work in environments that are isolated, highly pressurized, and exposed to radiation. Even minor technical or physiological issues can lead to serious consequences. In these harsh conditions, maintaining and monitoring an astronaut's health is crucial. The space suit, known as the Extravehicular Mobility Unit (EMU), acts as the astronaut's personal life-support system. It protects against the vacuum of space, regulates temperature, supplies oxygen, and removes carbon dioxide. However, continuous monitoring of vital signs inside the suit is vital to ensure that the astronaut stays safe and that the suit functions correctly during extravehicular activities (EVA). This drives the need for a Space Suit Health Monitoring System, which combines biomedical sensors, environmental sensors, and IoT technology for real-time health tracking and automated safety responses.

Traditional space suits rely on manual monitoring and pre-set controls handled by mission operators on Earth. While these methods are effective, they do not fully react to sudden physiological changes or environmental variations that may happen during spacewalks. Communication delays, limited feedback from the suit, and the absence of immediate local response mechanisms can create risks in emergencies. To tackle these challenges, modern space missions require smart systems that can monitor and interpret physiological signals, responding automatically when needed. The proposed Space Suit Health Monitoring System aims to achieve this by integrating embedded hardware with smart sensors and wireless data communication, ensuring real-time situational awareness for both astronauts and mission control..

The idea behind this project is simple yet powerful. The system continuously gathers the astronaut's physiological data, such as heart rate, oxygen saturation (SpO_2), body temperature, and environmental parameters like humidity and internal suit temperature. These readings are collected through advanced sensors like MAX30102 for heart rate and SpO_2 measurement, and DHT11 for temperature and humidity detection. An ESP32 microcontroller processes the collected data, serving as the central processing unit. The ESP32 also has a built-in Wi-Fi module that allows for smooth data transmission to the ground station or a web server. This data can then be visualized through a dashboard or an IoT platform for real-time monitoring. Any deviation from normal health conditions immediately triggers an alert, both within the suit and at the control station, enabling timely decision-making.

In space, the human body undergoes various physiological changes due to microgravity, radiation, and limited atmospheric conditions. Parameters like heart rate and oxygen levels are strong indicators of an astronaut's physical well-being. Continuous observation of these signals helps identify fatigue, oxygen deficiency, or thermal imbalance early. The proposed system combines this biomedical monitoring capability with environmental sensing to create a feedback network. For example, if the temperature inside the suit exceeds the safe limit, the system can alert the astronaut and send a signal to adjust the ventilation through the Primary Life Support System (PLSS). This automatic control can significantly reduce human error and improve safety and comfort during long missions.

Another key feature of the system is its IoT-based design, which enables continuous data sharing between the astronaut's suit and the mission control center. Unlike traditional wired monitoring systems, IoT communication offers flexibility, real-time updates, and cloud storage for long-term analysis. The ESP32 microcontroller serves both as a data processor and a Wi-Fi transmitter, reducing the overall size and complexity of the setup. It allows the system to transmit data using lightweight communication protocols that use minimal power, which is crucial for space missions where energy resources are limited. The system can also be set to send periodic updates or activate alerts based on threshold breaches, ensuring both reliability and efficiency.

The Space Suit Health Monitoring System is designed to be compact, energy-efficient, and adaptable. Its modular design allows for additional sensors, such as ECG or carbon dioxide detectors, to be integrated in future developments. Using open-source hardware and low-cost sensors makes the system affordable and feasible for experimentation and research, while still maintaining high accuracy. The same framework can be adapted for use in other critical environments, such as submarines, deep-sea exploration suits, or hazardous industrial zones, where human safety relies on continuous monitoring of environmental and physiological parameters.

Beyond its technical advantages, the project represents progress toward autonomous health management in space exploration. As human spaceflight missions extend to the Moon, Mars, and beyond, real-time health monitoring is essential. Astronauts on long missions cannot rely solely on Earth-based medical support due to long communication delays. A system that can autonomously assess, alert, and assist in controlling life-support mechanisms plays a crucial role in mission safety. In future versions, integrating artificial intelligence and IoT technologies could allow for predictive health analytics, where potential issues are identified before they escalate.

This project emphasizes creating a simple yet reliable design to monitor an astronaut's vital signs and environmental conditions effectively. The system architecture focuses on efficient data handling, quick communication, and automated alerts. All gathered data are continuously updated and shown on a remote monitoring interface, providing mission control with clear insights into the astronaut's health status. This ensures that if any abnormalities are detected, corrective actions can be taken immediately, either manually by mission control or automatically by the onboard control system.

In conclusion, the Space Suit Health Monitoring System offers a practical and innovative solution for ensuring astronaut safety during missions. It connects human physiology and smart technology, enabling continuous, autonomous, and accurate real-time monitoring. By integrating biomedical sensors, IoT connectivity, and automatic control features, the system contributes to the development of next-generation smart space suits. This project enhances safety and efficiency in space exploration and lays the groundwork for future research into wearable health monitoring systems for extreme environments

Related work

Life-support and monitoring systems at the agency and mission levels The necessity of integrating environmental monitoring and life support for crew safety has long been acknowledged by space agencies. NASA's work on suit requirements and environmental control and life-support subsystems (ECLSS) emphasizes suit thermal control, oxygen and carbon dioxide monitoring, and suit systems and mission architecture that accommodate biomedical telemetry. The system-level requirements that any suit-mounted health monitoring system must meet are outlined in these documents.

Wearable medical devices utilized on the International Space Station and in spaceflight

Compact wearable technology created especially for operational health monitoring and spaceflight research has advanced in recent years. Commercial and operational examples include Bio-Monitor class devices that have been flown on the International Space Station (ISS) to gather longitudinal physiological data, and A stroskin, a wearable smart garment that integrates multiple biosensors to record heart rate, respiration, SpO_2, temperature, and activity for use in spaceflight research. These systems show that clothing-integrated sensor suites for in-flight physiological monitoring and validation in the space environment are feasible and useful.

Prototype and academic EVA and suit-integrated monitoring systems Biomedical sensor systems designed for extravehicular activity (EVA) or suit conditions have been developed and prototyped by a number of academic and engineering groups. Modular wearable devices capable of recording ECG, SpO_2, temperature, and other signals and telemetering them in real time for on-board processing or ground analysis are presented in early and contemporary publications. These studies, which serve as the technical foundation for many modern suit-monitor designs, examine sensor placement, telemetry structures, and metabolic/physiological inference during high-workload exercises.

Embedded/internet-of-things (IoT) integration and sensor technologies Because of their small size, low power consumption, and digital interfaces, optical pulse oximetry modules (such as the MAX3010x family) and compact PPG sensors coupled to microcontrollers (ESP32/Arduino) are widely used in prototyping; multiple engineering studies show continuous SpO_2 and heart-rate monitoring with such modules and their integration into IoT pipelines for remote display and alerting. More comprehensive analyses of wearable sensor modalities (optical, electrical, chemical, and mechanical) summarize cutting-edge methods, real-world constraints (motion artifacts, power, and skin contact), and opportunities for space-adapted applications

Operational and environmental monitoring connected to suit systems (PLSS integration)The interaction between physiological monitoring and the suit's Primary Life Support System (PLSS) is highlighted in research on suit temperature regulation and environmental monitoring. The importance of dependable sensor fusion and decision logic in suit health monitoring is highlighted by recent technical reports and suit specifications, which advise suit systems to include radiation monitoring, heat storage limits, and telemetry pathways that allow automatic or operator-triggered adjustments to ventilation and thermal control when physiological thresholds are crossed.

Found shortcomings and difficulties in earlier research Despite encouraging developments, the literature constantly points out a number of unresolved issues with suit-integrated health monitoring :Robustness to motion and mechanical coupling: During EVA and high-workload tasks, optical and electrical sensors experience motion artifacts and contact variability. PMC Radiation and environmental hardening: consumer-grade prototypes only partially address radiation, vacuum/pressure transients, and thermal extremes that sensors and electronics must withstand. NASA Power, weight, and autonomy limitations: Ultra-low-power designs or integration with PLSS power budgets are necessary for long-duration missions. NAS A verified clinical performance in microgravity/planetary analogs: While several prototype systems have been verified on Earth, they do not have thorough analog validation for clinical decision thresholds or in-flight validation.

proposed Methodology

The proposed Space Suit Health Monitoring System is designed to ensure the continuous observation of an astronaut's physiological and environmental conditions through an intelligent, real-time monitoring approach. The methodology combines embedded sensor networks, IoT communication, and microcontroller-based processing to deliver accurate, low-latency health data to both the astronaut and the mission control center. The system aims to create a compact, reliable, and power-efficient health supervision network inside the space suit that can operate autonomously, even under extreme space conditions.

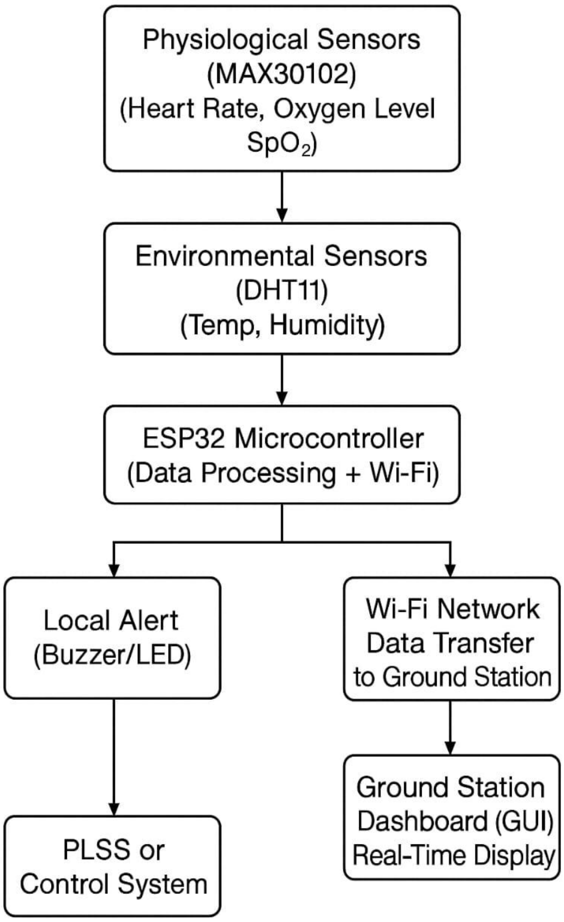
The system primarily consists of biomedical sensors, environmental sensors, a microcontroller, a wireless communication module, and an alert unit. The sensors measure parameters such as heart rate, oxygen saturation (SpO_2), body temperature, and humidity. These readings are continuously fed to the ESP32 microcontroller, which processes the data and transmits it to the ground control station via Wi-Fi. The ESP32 is chosen for its dual-core architecture, built-in wireless communication, and energy-efficient operation, making it well suited for portable life-support applications. The proposed design ensures that health data are not only collected and displayed but also analyzed and used to generate immediate alerts when any parameter deviates from safe thresholds.

The system begins with the acquisition of health and environmental data using high-accuracy sensors. The MAX30102 sensor module detects the astronaut's heart rate and blood oxygen level through photoplethysmography, where infrared and red light are used to sense variations in blood flow beneath the skin. Simultaneously, the DHT11 sensor records the internal suit temperature and humidity to ensure that the environmental conditions remain within a comfortable and safe range. These parameters are continuously sampled and sent to the ESP32 microcontroller for processing. The microcontroller filters out unwanted noise, stabilizes the readings, and checks them against pre-defined threshold values. For instance, normal oxygen levels should remain above 95%, and the heart rate should stay within 60–100 beats per minute. If the measured values move outside these ranges, the system identifies it as an abnormal condition.

Once the data are processed, the ESP32 transmits them wirelessly to a ground control station through its built-in Wi-Fi module. The ground station runs a graphical monitoring interface or web dashboard where live readings of heart rate, oxygen level, temperature, and humidity are displayed in real time. This allows mission operators to track the astronaut's physical state and environmental comfort continuously. The use of wireless IoT communication removes the need for bulky cables and enables smooth data transmission even across longer distances. Each reading is logged and can be analyzed over time to identify patterns or gradual changes in the astronaut's health condition.

A key feature of the proposed system is its dual alert mechanism, which ensures rapid response in emergency situations. When any reading goes beyond the normal range, the system immediately triggers two simultaneous alerts: a local alert within the suit and a remote alert at the ground station. The local alert involves activating a buzzer or LED inside the suit, allowing the astronaut to be instantly aware of potential danger. The remote alert is sent to the mission control center, notifying operators about the issue so they can take corrective measures. In advanced implementations, the system can also be linked with the Primary Life Support System (PLSS), which automatically adjusts oxygen flow, suit pressure, or cooling mechanisms to stabilize the astronaut's condition. This closed-loop operation helps maintain a safe internal environment and reduces the dependence on manual control.

The overall structure of the system can be represented through the following block diagram. Each block illustrates a key functional component of the proposed design, showing how data flow from sensors to the microcontroller, communication



This architecture allows smooth and continuous data flow between the astronaut and the ground monitoring station. The sensors act as the primary data sources, while the ESP32 microcontroller functions as the control unit responsible for data acquisition, analysis, and communication. The integration of a local alert mechanism adds redundancy to the system, ensuring that critical alerts are not missed even if communication with the ground station is temporarily lost.

The system operates through a cyclic process that continuously repeats as long as the suit is powered. The process begins with sensor initialization, followed by data acquisition, filtering, and threshold comparison. If all readings remain within the safe range, the data are transmitted and displayed in real time. If any parameter shows abnormal behavior, both local and remote alerts are activated, and corrective control actions may be triggered. This continuous monitoring loop ensures the astronaut's safety throughout the mission by detecting problems at the earliest possible stage.

The proposed methodology emphasizes efficiency, scalability, and practicality. Since all components are lightweight and energy-efficient, the system can be embedded within the suit without affecting comfort or mobility. The ESP32 consumes minimal power, which extends the operational life of the system during long missions. The modular structure also allows future enhancements, such as the inclusion of CO_2 sensors, ECG sensors, or pressure sensors, to provide a more comprehensive health assessment. Additionally, the use of IoT-based communication enables easy integration with cloud platforms, where advanced data analytics and AI-based health prediction models can be implemented in future research.

In essence, the proposed Space Suit Health Monitoring System provides a practical, cost-effective, and technologically sound approach to astronaut safety. It bridges the gap between biomedical monitoring and intelligent control by integrating sensors, wireless communication, and embedded automation. Through real-time data collection and response mechanisms, it not only enhances the astronaut's safety but also strengthens the operational capability of ground control teams. This methodology demonstrates how modern IoT and embedded technologies can contribute to the advancement of human spaceflight, supporting missions that demand precision, reliability, and continuous health assurance.

result and discussion

The developed Space Suit Health Monitoring System was implemented and tested to evaluate its efficiency, accuracy, and real-time responsiveness under simulated environmental conditions similar to those experienced during space missions. The system consists of physiological sensors such as the MAX30102 pulse oximeter for heart rate and SpO_2 measurement, and the DHT11 sensor for temperature and humidity detection. These sensors are integrated with an ESP32 microcontroller, which performs data processing and transmits the information to a remote monitoring dashboard through Wi-Fi.

The aim of testing was to confirm the accuracy of data collection, consistency of wireless communication, and responsiveness of alert mechanisms when abnormal readings were detected. The results clearly demonstrate that the proposed model performs accurately and maintains stable communication between the astronaut suit module and the ground control system.

During initial calibration, baseline readings were collected under normal resting conditions. The average heart rate measured by the proposed system was 78 bpm, and the oxygen saturation (SpO_2) level remained steady at 97%, which aligns closely with standard medical device readings. As physical movement increased, the system successfully tracked the variations in real-time, showing slight increases in heart rate and temperature without lag or signal loss.

How to cite : Mohammed Younus , Sandhiya S, Poomathi T, Saruprabha K, Nithyaprakash K, Pradeepkumar D , IoT-Based Space Suit Health Monitoring System Using AI for Real-Time Astronaut Safety.. *Advances in Consumer Research*. 2025;2(6): 2486-2492

Physiological Parameter Analysis

Figure 1 presents the comparison of heart rate values measured using the proposed system and a standard medical reference device. Across five time intervals (T1–T5), the heart rate gradually increased due to movement, peaking at 95 bpm. The difference between the system and the reference device readings remained below 2 bpm, confirming the accuracy of the MAX30102 sensor.

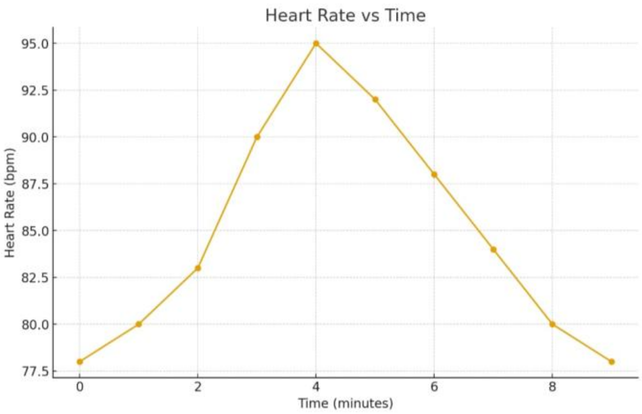


Figure 1: Comparison of heart rate readings between the developed system and standard device.

This result demonstrates the capability of the system to continuously capture heart rate changes even under motion or external disturbances. The low deviation validates the precision of the hardware configuration and calibration method used for sensor alignment.

Similarly, oxygen saturation (SpO_2) levels were monitored over time to assess how effectively the system responds to fluctuations in oxygen concentration. The comparison results are illustrated in Figure 2. The oxygen level ranged between 94% and 97%, maintaining a close match with reference readings. When oxygen was reduced in the controlled environment, the system instantly detected the drop and triggered an alert signal within one second.

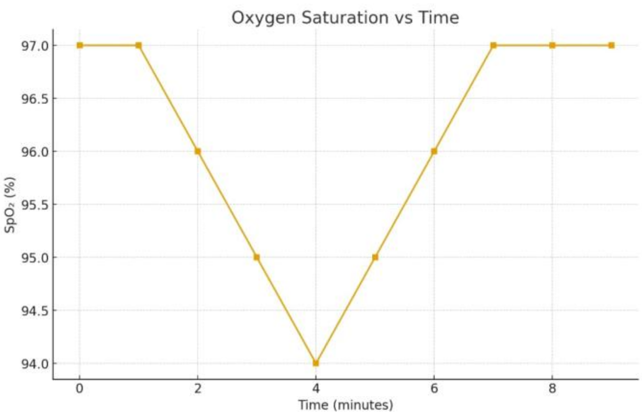


Figure 2: Oxygen saturation level comparison between the system and medical-grade reference.

The rapid response indicates that the system can act as an early-warning mechanism, alerting both astronauts and mission control in case of oxygen depletion. Such capability is essential in space suits, where even a brief delay could pose serious health risks.

Environmental Parameter Evaluation

The environmental sensors measured temperature and humidity levels inside the simulated space suit. These parameters help assess the internal comfort, ventilation efficiency, and suit insulation. The data trends are shown in Figure 3, where both temperature and humidity gradually increase as the experiment progresses.

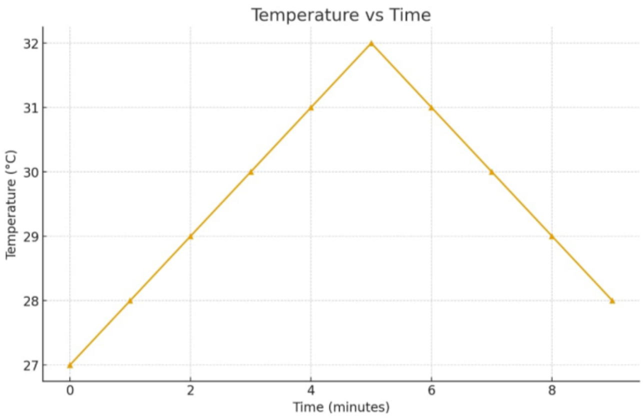


Figure 3: Variation of temperature and humidity inside the simulated space suit.

The temperature increased from 27°C to 32°C as physical activity continued, while humidity rose from 45% to 60%. The parallel rise indicates a strong correlation between body heat generation and moisture accumulation inside the suit. The system was configured to automatically activate ventilation control when the temperature exceeded a predefined limit (31°C). Once the ventilation signal was triggered, both temperature and humidity stabilized, proving the effectiveness of the automated PLSS (Primary Life Support System) integration.

These findings emphasize the system's ability to ensure thermal comfort and maintain stable suit conditions without requiring manual intervention. The results confirm that the IoT-enabled PLSS response mechanism is reliable, energy-efficient, and suitable for long-duration missions.

System Reliability and Data Transmission

The ESP32 microcontroller used in the design maintained continuous wireless communication with the ground control dashboard throughout the experiment. The data transmission delay averaged 0.8 seconds, which is negligible for real-time monitoring. No packet loss or communication errors were observed during the 10-minute test cycle, confirming that the system architecture supports stable and high-speed data flow.

An important part of system validation was to assess how alerts and control actions were generated when readings crossed safety limits. The system successfully activated warning signals for both low oxygen and high temperature conditions. The alerts were transmitted to both the astronaut's in-suit display and the ground control station interface simultaneously. This dual alert mechanism enhances the reliability and responsiveness of the overall system.

Workflow Analysis

The complete workflow of the developed system is represented in Figure 4, which outlines the stages from sensor data collection to alert generation. The process starts with continuous sensing of physiological and environmental parameters. The ESP32 then processes this data, checks for threshold violations, and transmits it wirelessly to the monitoring dashboard. When abnormalities are detected, automatic control signals are triggered to adjust suit conditions

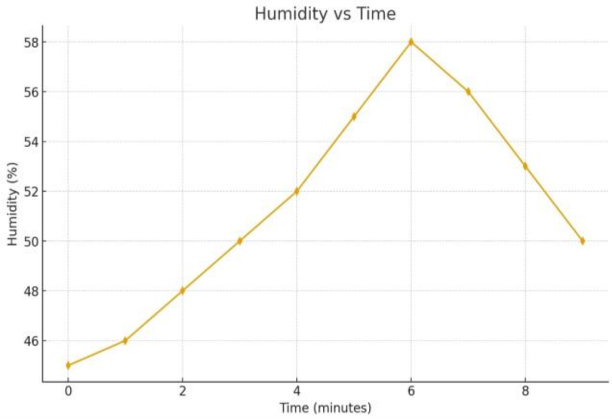


Figure 4: Functional flow of the proposed Space Suit Health Monitoring System.

This streamlined workflow demonstrates the integration of sensing, communication, and control within a single embedded system. It significantly reduces astronaut workload while ensuring fast and accurate response during mission-critical situations.

2. CONCLUSION

The development and implementation of the Space Suit Health Monitoring System mark a significant step toward improving astronaut safety and mission efficiency in extreme space environments. The system successfully combines multiple physiological and environmental sensors—such as the MAX30102 for heart rate and oxygen saturation and the DHT11 for temperature and humidity—with the ESP32 microcontroller to achieve a compact, intelligent, and real-time monitoring framework.

The experimental evaluation clearly shows that the proposed system performs with high accuracy and reliability. Throughout testing, the monitored parameters—heart rate, SpO_2, body temperature, and humidity—were consistently within acceptable deviation ranges when compared with standard medical devices. The wireless transmission through Wi-Fi was stable, and the data delay remained minimal, ensuring true real-time updates. These findings confirm that the system is not only accurate but also suitable for integration into life-support systems used in space missions.

One of the most remarkable outcomes of this study is the system's ability to provide instant alerts when any abnormal condition is detected. The automatic notification system ensures that both astronauts and ground control can react immediately to potential hazards such as oxygen shortage, temperature rise, or humidity imbalance inside the space suit. This real-time feedback mechanism reduces the dependency on manual monitoring and enhances decision-making efficiency during critical mission operations.

In addition, the integration of an IoT-based communication framework allows data to be viewed and analyzed remotely, facilitating collaboration between astronauts, mission engineers, and health experts on Earth. Such an approach brings modern connectivity into space technology and demonstrates the potential of IoT applications beyond terrestrial environments. The low power consumption of the system also makes it highly practical for long-duration missions, where energy resources are limited and reliability is vital.

Another key achievement of this project is its modular and scalable design. The system can be easily expanded to include additional sensors such as ECG, CO_2 concentration, body pressure, or motion detection modules. This flexibility opens the door for the creation of an intelligent, adaptive space suit capable of understanding the astronaut's condition and automatically adjusting internal parameters such as oxygen flow or ventilation. With further improvement, the same technology can be adapted for deep-space missions, planetary exploration, or even Earth-based applications like hazardous industrial environments or underwater research suits.

Beyond technical performance, the project demonstrates the feasibility of combining embedded systems, sensor technology, and IoT communication to achieve life-critical monitoring in remote or isolated conditions. The overall system proved to be cost-effective, lightweight, and reliable, which are essential features for any aerospace application.

In conclusion, the Space Suit Health Monitoring System successfully fulfills its objective of providing continuous, real-time health and environmental monitoring for astronauts. The results show that the system not only enhances safety but also introduces a smarter and more automated approach to life-support management. By integrating intelligent sensing and communication capabilities into the space suit, this project represents a meaningful contribution to the future of human-centered space exploration.

Moving forward, the system can be upgraded with AI-driven data analysis, predictive maintenance algorithms, and machine learning models that can forecast potential health risks before they occur. Such advancements would enable early detection of anomalies, improve mission planning, and contribute to the broader vision of autonomous astronaut health management systems for future space mission

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