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ESP32-POWERED REAL TIME PHARMACEUTICAL CONDITION MONITORING AND CONTROL SYSTEM USING IoT

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ABSTRACT :

The "ESP32-Powered Real Time Pharmaceutical Condition Monitoring and Control System using IoT" is a state-of-the-art embedded solution designed to uphold precise environmental conditions within pharmaceutical storage and production facilities. Central to its operation is the ESP32 microcontroller, which supports two operational modes: Manual and Automatic. In Manual Mode, operators can directly manage the heating and cooling systems according to their specific requirements. Conversely, in Automatic Mode, the system autonomously regulates the environment by activating the cooling system when temperatures rise above set thresholds and engaging the heater when humidity levels drop below acceptable limits. In addition to environmental control, the system incorporates advanced safety mechanisms to protect pharmaceutical assets and infrastructure. It includes real-time alert functionalities for detecting critical issues such as fires, gas leaks, elevated temperatures, and high humidity. Upon detecting a gas leak, the system automatically activates a DC exhaust fan to ventilate the area and minimize potential risks.

KEYWORDS : Pharmaceutical monitoring, IoT technology, ESP32 microcontroller, real- time sensing, temperature control, humidity regulation, gas leakage detection, remote monitoring.

1. LITERATURE SURVEY

The Internet of Things (IoT) has emerged as a transformative technology, enabling seamless communication and interaction between physical devices through the integration of sensors, connectivity modules, cloud platforms, and data analytics. Its applications span across diverse domains such as agriculture, healthcare, environmental monitoring, industrial automation, and pharmaceutical systems, where precision, reliability, and real-time responsiveness are paramount [1]. In pharmaceutical monitoring, maintaining optimal environmental conditions such as temperature, humidity, and air quality is critical to preserving the efficacy and safety of sensitive drugs. IoT facilitates this by providing automated alerts and adjustments, ensuring that deviations from desired thresholds are promptly addressed [2]. In agriculture, IoT systems are widely used for monitoring soil moisture, temperature, and other parameters, which are equally relevant in pharmaceutical storage environments. Stable conditions must be maintained to prevent the degradation of pharmaceutical products [3]. The architectural framework of IoT, comprising perception, network, and application layers, supports scalable and flexible deployments, making it particularly suitable for compliance-driven industries like pharmaceuticals [1]. Even basic IoT implementations using simple sensors like the DHT11 have demonstrated their ability to provide reliable environmental monitoring, serving as a foundation for more advanced systems powered by microcontrollers such as the ESP32 [4][5]. The ESP32 microcontroller stands out due to its integrated Wi-Fi and Bluetooth capabilities, enabling real-time data transmission to cloud dashboards for remote monitoring and control [6]. In healthcare and pharmaceutical applications, IoT systems equipped with intelligent alert mechanisms notify users when environmental conditions exceed safe thresholds, thereby safeguarding drug efficacy and safety [6][7]. Smart pharmacy solutions further enhance this by incorporating cloud-based logging and analytics, providing transparent and traceable records of environmental data [6]. From a safety perspective, IoT systems are increasingly being integrated into fire and gas detection setups. These systems can autonomously trigger alarms and ventilation mechanisms, mitigating risks in pharmaceutical storage facilities where chemical spills or gas leaks can pose significant hazards [11]. For instance, gas-based ventilation systems automatically activate upon detecting unsafe gas concentrations, ensuring indoor air quality is maintained [12]. Industrial IoT systems also leverage cloud-linked devices to push real-time notifications via SMS or app-based alerts, enabling immediate responses to critical events [13]. Low-cost microcontrollers like the ESP8266 have been employed to develop real-time temperature monitoring and control systems, demonstrating that budget-friendly solutions can still achieve accuracy and effectiveness [13]. While these boards may lack the processing power or advanced features of the ESP32, they validate the feasibility of IoT in scalable and cost-effective deployments [13].

2. INTRODUCTION

Pharmaceutical products are highly susceptible to environmental factors such as temperature, humidity, and exposure to hazardous gases. Even slight variations in these parameters can compromise the quality and efficacy of drugs, posing significant health risks and resulting in substantial financial losses. Ensuring the stability of these conditions is critical to maintaining the integrity of pharmaceuticals throughout their lifecycle. The World Health Organization (WHO) emphasizes that proper storage and handling practices are vital to ensuring the safety and compliance of pharmaceutical products. As the industry expands and evolves, there is an increasing demand for advanced, real-time monitoring system capable of maintaining environmental stability and ensuring safety. Traditional methods, which often rely on manual inspections or standalone sensors, are inadequate due to their inability to provide real-time data transmission and automated decision-making. These approaches are prone to human error, time-consuming, and incapable of responding promptly to adverse conditions. To address these limitations, the integration of Internet of Things (IoT) technologies and embedded systems has emerged as a transformative solution. This project harnesses the capabilities of the ESP32 microcontroller, IoT connectivity, and intelligent control mechanisms to design a robust, automated system for real-time monitoring and regulation of pharmaceutical conditions. By leveraging IoT-enabled sensors, cloud platforms, and smart alert systems, this solution ensures precise environmental control while minimizing risks associated with human intervention. In the subsequent sections, we explore the technical architecture of this system, detailing its components, functionality, and advantages. Through this analysis, we aim to demonstrate how cutting-edge technology can be seamlessly integrated into pharmaceutical practices to enhance safety, efficiency, and sustainability. This innovative approach not only addresses current challenges but also sets a foundation for future advancements in smart healthcare and pharmaceutical management. The primary goal of this project is to design and implement a cutting-edge system that ensures the stability of pharmaceutical storage environments while addressing potential safety risks through intelligent sensing, automated actuation, and seamless cloud integration. The system continuously monitors critical environmental parameters such as temperature, humidity, gas concentrations, and the presence of fire in real-time. It operates in two distinct modes: Manual Mode, which provides users with direct control over cooling and heating systems, and Auto Mode, where the system autonomously adjusts environmental conditions based on predefined thresholds. In the event of hazardous conditions, the system triggers alerts and notifications to ensure timely intervention. For instance, if a gas leak is detected, the system automatically activates a DC exhaust fan to ventilate the area and reduce risks. Real-time sensor data is displayed on an LCD screen for local monitoring, while all readings and system statuses are uploaded to a cloud platform (IOTY) for remote access, real-time visualization, and historical data logging. This combination of local and cloud-based monitoring ensures comprehensive oversight and enhances the reliability of pharmaceutical storage and safety management.

IMPLEMENTATION

The system begins real-time environmental monitoring by utilizing a network of sensors linked to the ESP32 module. These sensors are responsible for measuring critical parameters such as temperature, humidity, air quality, and atmospheric pressure within pharmaceutical storage areas. This ensures adherence to regulatory standards like Good Manufacturing Practices (GMP) and FDA guidelines. Specific sensors, including the DHT22 for temperature and humidity, MQ135 for air quality, and BMP280 for pressure, gather data at regular intervals. The ESP32 module processes this information and temporarily stores it locally for immediate access and analysis. To maintain precision, the system implements sensor calibration procedures during the initial setup, followed by periodic recalibration as needed to ensure long-term accuracy and reliability. Before being sent to the cloud for further analysis, the sensor data undergoes preprocessing to ensure accuracy and usability. The raw readings from the sensors are first converted into meaningful values, such as transforming voltage outputs from the air quality sensor into parts per million (ppm). To minimize the impact of sensor noise, data smoothing techniques like moving average filters are applied, reducing unwanted fluctuations. Thresholds for each environmental parameter are established based on pharmaceutical industry standards, such as a temperature range of 15°C–25°C and a humidity range of 30%–60%. If any parameter exceeds its predefined threshold, the system identifies the data point as an anomaly and flags it for immediate attention or corrective action. After preprocessing, the data is transmitted in real-time to a custom cloud-based web server using HTTP protocols. The server is developed using HTML and PHP, enabling dynamic webpage creation and secure data management. The ESP32 sends sensor readings to the server via POST requests, which are processed by PHP scripts. These scripts then store the data in a MySQL database for long-term logging and analysis. This system allows users to access both real-time and historical environmental data through any web browser. The HTML interface is designed to present temperature, humidity, air quality, and pressure readings in a clear and user-friendly format. On the server side, alerts are generated whenever a sensor reading exceeds the predefined thresholds. Automated email notifications or alerts displayed on the web interface are triggered by PHP scripts, ensuring prompt responses from administrators to address any anomalies. The entire process of data collection, processing, and transmission to the cloud is completed in under one second per reading, ensuring minimal latency and enabling real-time monitoring. The system is engineered to operate on a low-power 5V supply and employs event-driven logic, activating only when new data is acquired or when a parameter exceeds its predefined threshold. To optimize power consumption, the ESP32 transitions into deep sleep mode whenever it is not actively processing data. In the event of communication failures or sensor malfunctions, robust error-handling mechanisms are in place. These mechanisms either retry the operation or log the issue for later manual intervention, ensuring the system remains stable and reliable even during hardware faults or network interruptions.

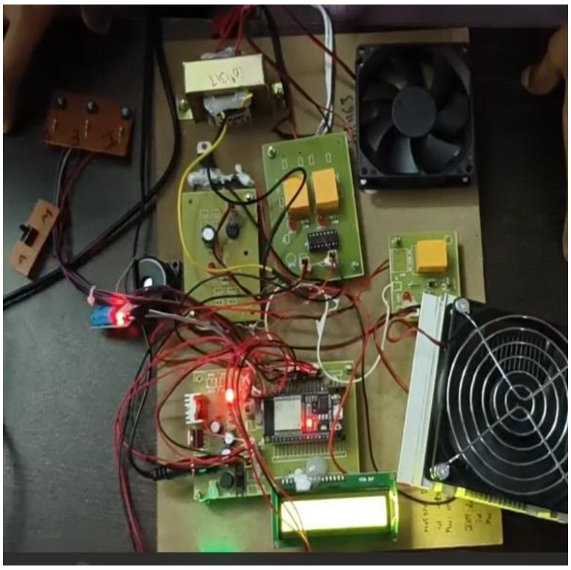

Fig 4.1 : Implementation of Pharmaceutical Condition Monitoring and Control System

BLOCK DIAGRAM

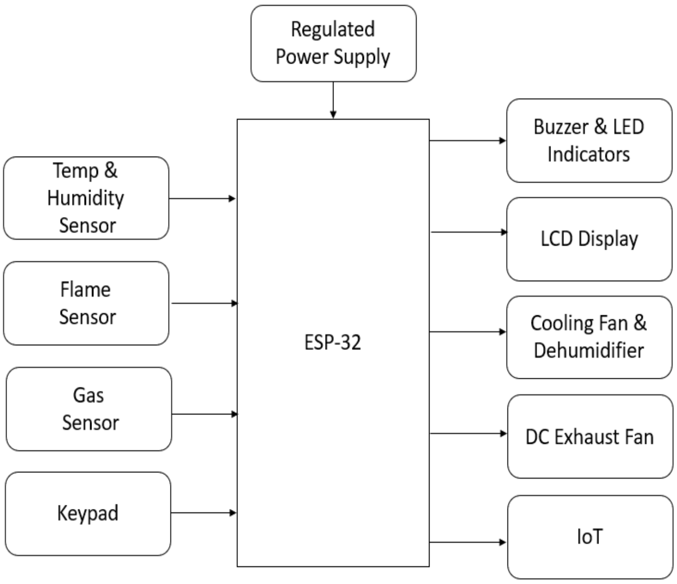

Fig 5.1: Block Diagram of Pharmaceutical Condition Monitoring and Control System.

The block diagram represents a smart environmental monitoring system built around an ESP-32 microcontroller. It uses sensors for temperature, humidity, flame, and gas detection, alongside a keypad for user input. The system processes data to control outputs like buzzers, LEDs, fans, dehumidifiers, and an LCD display, while IoT integration enables remote access, ensuring real-time monitoring and automated responses for safety and efficiency.

WORKING:

The functionality of the ESP32-powered real-time pharmaceutical condition monitoring and control system centers on real-time sensing, intelligent data processing, and automated control to ensure safe storage conditions for pharmaceuticals. The ESP32 microcontroller continuously gathers input from various sensors, including a DHT22 sensor for temperature and humidity, an MQ-3 gas sensor for detecting hazardous gases, and a KY-026 flame sensor for identifying fire hazards. These sensors monitor environmental parameters within a pharmaceutical storage unit, ensuring that all conditions remain within acceptable limits. Once the data is collected, the ESP32 processes it to determine whether any parameter exceeds predefined safety thresholds. If unsafe conditions such as elevated temperatures, the presence of harmful gases, or fire—are detected, the system activates local alerts, such as a buzzer and LED indicators, while simultaneously triggering appropriate actuators. For instance, a cooling fan, heater, or DC exhaust fan may be engaged to restore optimal environmental conditions. Additionally, the system incorporates a keypad that allows users to input customized temperature settings, which is particularly useful for storing sensitive drugs like insulin and vaccines, typically requiring a temperature range of 2°C to 8°C. A Web/Auto mode selector provides flexibility, enabling users to operate the system manually or automatically based on their preferences. A key feature of this project is its ability to transmit real-time sensor data to a web server hosted on platforms like GoDaddy. The ESP32 sends data to the server using HTTP POST requests via its integrated Wi-Fi module. The server, built using PHP and HTML, stores the transmitted data in a MySQL database and displays it on a custom-designed web dashboard created with HTML, PHP, and CSS. This dashboard allows users to remotely monitor all storage parameters in real time through any web browser, receive notifications, and analyze historical trends. By offering an affordable and scalable solution, this system serves as a cost-effective alternative to expensive SCADA systems, making it particularly suitable for small and medium-scale pharmaceutical facilities where precise storage conditions are critical to prevent drug spoilage.

Fig 6.1: LCD Display in Auto Mode

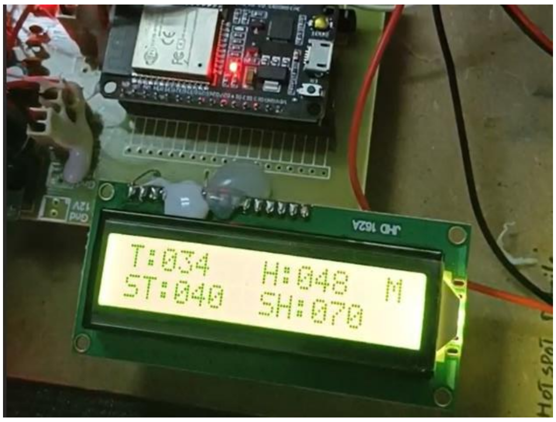

Fig 6.2: LCD Display in Manual/Web Mode

7. APPLICATIONS AND FUTURE SCOPE

The ESP32-powered real-time pharmaceutical condition monitoring and control system finds valuable applications in various sectors where precise environmental control is essential. It is particularly well-suited for pharmaceutical warehouses, hospital drug storage facilities, and vaccine distribution centers, ensuring that medicines—especially temperature-sensitive products like insulin and vaccines—are stored under optimal conditions. Medical laboratories and research institutions can also leverage this system to maintain ideal environments for preserving biological samples and reagents, safeguarding their integrity and usability. Furthermore, the system offers a cost-effective alternative to SCADA systems, making it an accessible solution for small and medium-scale pharmaceutical companies that lack the resources for expensive automation technologies. Looking ahead, the system's potential for future development is vast. Integrating Edge AI capabilities could enable predictive maintenance by analyzing data patterns to anticipate failures and optimize control actions proactively. Incorporating battery backup systems would ensure uninterrupted operation during power outages, enhancing reliability in critical scenarios. Additionally, the system can be scaled to monitor multiple zones or storage rooms from a centralized platform, streamlining oversight across larger facilities. Upgrades such as voice control or touch-screen interfaces could further improve user accessibility and ease of operation. These proposed enhancements would significantly boost the system's reliability, intelligence, and adaptability, making it an even more robust tool for pharmaceutical and healthcare environments. By addressing current limitations and expanding its functionality, the system can continue to meet the evolving demands of these industries, ensuring safer and smarter environmental monitoring solutions.

8. CONCLUSION

The implementation of the ESP32-powered real-time pharmaceutical condition monitoring and control system using IoT presents a smart, efficient, and dependable solution for maintaining optimal environmental conditions in pharmaceutical storage facilities. By combining advanced sensors with the capabilities of the ESP32 microcontroller and IoT technology, the system effectively tracks critical parameters such as temperature, humidity, gas leaks, and fire hazards, ensuring prompt responses and preventive actions. The inclusion of dual operation modes—Auto and Manual—enhances flexibility, enabling both automated environmental regulation and user-defined manual adjustments when necessary. The system's ability to autonomously activate cooling or heating devices based on sensor data minimizes human intervention, helping preserve the efficacy of drugs sensitive to temperature and humidity fluctuations. Additionally, safety features like automatic exhaust fan activation for gas leaks and real-time fire detection alerts contribute to creating a secure storage environment. Real-time data logging to the IOTY cloud platform, along with local display on an LCD screen, ensures complete transparency and accessibility of environmental data for audits, remote supervision, and compliance purposes. This functionality addresses the limitations of traditional pharmaceutical monitoring methods by integrating automation, IoT connectivity, and multi-layered safety mechanisms. The result is a scalable and cost-effective solution tailored for pharmaceutical industries, retail pharmacies, and healthcare institutions seeking to modernize their environmental monitoring practices while adhering to regulatory standards. Looking ahead, the project holds significant potential for further development and real-world deployment. Future enhancements could include mobile app control, AI-driven predictive analytics, or integration with building management systems, making the system even more versatile and powerful. By operating in both manual and automatic modes, the system ensures adaptability and reliability in regulating temperature, humidity, gas levels, and fire hazards. Its seamless integration with IoT cloud platforms enables remote monitoring, instant alerts, and secure data logging—features that are crucial for regulatory compliance and quality assurance. With its cost-effective design, embedded safety measures, and scalability, this project represents a robust advancement toward safer and smarter pharmaceutical environments. The incorporation of IoT into pharmaceutical monitoring is not merely a technological leap but a necessity in today's compliance-driven and safety-critical landscape. As microcontrollers and cloud services continue to evolve, real-time monitoring and control have become increasingly accessible and efficient, paving the way for smarter storage and distribution networks in the pharmaceutical industry. Moreover, the system's adaptability extends beyond pharmaceuticals to other sectors requiring precise environmental control, such as food storage, biotechnology research, and chemical manufacturing. By leveraging advancements in IoT, AI, and cloud computing, this system exemplifies how technology can transform traditional practices into intelligent, data-driven solutions. Its modular architecture allows for customization and expansion, ensuring it remains relevant as new technologies emerge. Ultimately, this project not only addresses current challenges but also sets a foundation for future innovations, reinforcing its role as a cornerstone in the evolution of smart environmental monitoring systems.

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