Development of IoT-Based Smart Laboratory System for Enhanced Safety and Efficiency

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ABSTRACT

The IoT-Based Smart Laboratory System aims to enhance laboratory safety and efficiency. This project integrates a robotic arm, various sensors, and a user-friendly mobile application for remote monitoring and control. Key features include contactless pipetting, real-time environmental monitoring, and automated adjustments to maintain optimal laboratory conditions. The system employs an ESP-WROOM-32 microcontroller, MQ-2 gas sensor, DHT22 temperature and humidity sensor, LDR sensor, and a high-torque robotic arm to achieve its objectives. Experimental results demonstrate improved laboratory automation, reduced risks for personnel, and efficient resource utilization, marking a significant advancement in smart laboratory technology.

Keywords: IoT, Smart Laboratory, remote monitoring, remote control, contactless pipetting

INTRODUCTION

The COVID-19 pandemic brought unprecedented challenges to laboratory operations worldwide, exposing healthcare professionals and researchers to significant risks during routine tasks. These challenges underscored the urgent need for solutions that minimize physical contact while ensuring operational efficiency. Traditional laboratories often rely on manual adjustments to equipment such as incubators, freezers, and lighting systems, which are resource-intensive and pose risks to personnel. Additionally, tasks like pipetting, monitoring environmental parameters, and adjusting settings are labor-intensive, exposing workers to potential hazards and limiting reproducibility and scalability.

While Internet of Things (IoT) technologies have emerged as transformative tools for enhancing safety and efficiency across various domains, previous IoT-based laboratory solutions are often constrained by limited integration between robotics and sensor systems, inadequate power management, and high implementation costs. For instance, Wan Faizura et al. [1] utilized the Blynk application to control a robotic arm, showcasing the benefits of seamless communication between IoT devices. However, the project involved a robotic arm with only two grippers, which is insufficient for handling laboratory pipettes. Additionally, the lack of integrated sensors limits its functionality as a comprehensive smart laboratory system. Similarly, Ernesto Ladanza et al. [2] developed a Bluetooth-controlled robotic arm but encountered constraints in scalability and connectivity, as the system relied solely on local communication, restricting its potential for remote operations.

In another study, Asad [3] employed the Raspberry Pi and Arduino UNO with temperature and humidity sensors for agricultural monitoring. Although the system effectively controlled environmental conditions using IoT, it did not incorporate robotic components, such as an arm for handling delicate laboratory equipment, making it unsuitable for laboratory automation. Furthermore, the use of separate Wi-Fi modules increased hardware complexity and cost. Hashim et al. [4] designed an air-quality monitoring system using IoT, integrating sensors for gas detection and environmental data logging. While effective in real-time monitoring, the system lacked an automation component to respond dynamically to detected anomalies, limiting its ability to perform autonomous adjustments in laboratory settings.

Poonia et al. [5] proposed an IoT-based smart helmet for detecting potential COVID-19 infections. The system utilized thermal and optical cameras to identify individuals with elevated body temperatures, integrating Blynk for remote monitoring. Despite its innovative approach, the project was limited to infection detection and lacked broader applications for laboratory automation. Barik et al. [6] implemented an IoT-based environmental control system for agricultural purposes using the ThingSpeak platform. The system managed temperature and water levels effectively but did not include robotic functionalities or support laboratory-specific applications. Additionally, the reliance on external cloud services raised concerns about data privacy and real-time responsiveness.

Liu et al. [7] designed a robotic system for remote operation during the COVID-19 pandemic, incorporating Bluetooth and Wi-Fi communication. However, the project faced challenges in power management, as the robotic arm’s performance was constrained by limited torque and battery life. These challenges highlight the importance of integrating efficient power management systems in robotic applications.

Addressing these shortcomings, this project proposes a smart laboratory system that integrates IoT technologies and robotic automation, aiming to develop a cost-effective, efficient, and user-friendly solution for seamless laboratory operations with minimal human involvement. A robotic arm is developed for contactless pipetting, supported by the integration of sensors to monitor essential environmental parameters, including temperature, humidity, gas concentration, and light intensity. Furthermore, remote monitoring and control are facilitated through a mobile application that provides real-time data visualization and interaction capabilities.

System Design and Testing

The IoT-Based Smart Laboratory System is designed to seamlessly integrate robotics, environmental monitoring, and remote control functionalities, providing a comprehensive solution for laboratory automation. At its core, the system utilizes an ESP-WROOM-32 microcontroller, which acts as the central processing unit, facilitating communication between the sensors, actuators, and a mobile application. Input is gathered from sensors, including the DHT22 for temperature and humidity monitoring, the MQ-2 for detecting gas concentration and smoke, and the LDR for light intensity measurement. These sensors provide real-time environmental data that are processed by the microcontroller to ensure optimal laboratory conditions.

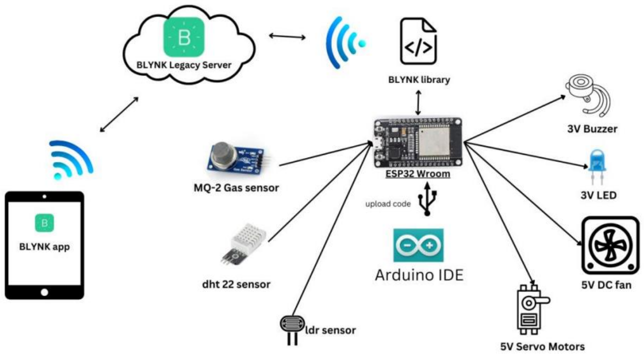


Fig. 1 System architecture of the IoT-Based Smart Laboratory System

The robotic arm, a key component of the system, is designed with six degrees of freedom and powered by high-torque MG996R servo motors, enabling precise and stable movements required for pipetting tasks. To accommodate heavier loads and improve stability, additional grippers and springs are integrated into the arm’s design. An external power supply ensures consistent performance and protects the microcontroller from overloading. The MB-102 power supply module efficiently converts input power to 3.3V and 5V outputs, catering to the needs of various components, while a logic level converter maintains compatibility between the microcontroller’s 3.3V logic and the 5V requirements of some actuators.

The Blynk app provides an intuitive platform for users to remotely monitor sensor readings, control the robotic arm, and override automatic operations as needed. System interactions are dynamic, with sensor data driving automated responses such as activating the robotic arm, fan, or LED to maintain environmental stability. Users are also empowered to manually intervene through the application, enabling flexible and responsive laboratory management.

The proposed IoT-based smart laboratory system went through extensive testing to evaluate its functionality, reliability, and efficiency. The system components, including the robotic arm, sensors, and Blynk-based mobile application, were tested in controlled laboratory environments. Testing included calibration of sensors such as DHT22 (temperature and humidity), MQ-2 (gas concentration), and LDR (light intensity) to ensure accurate readings. The robotic arm's pipetting capabilities were evaluated for precision and stability.

The system was tested for real-time data monitoring and control using Blynk application. Environmental conditions, such as temperature and humidity, were altered deliberately, and the system's ability to respond by activating the fan, buzzer, and LED was monitored. Each experiment underwent multiple cycles of operation to assess durability and minimize failure rates. The system's integration was tested by performing simultaneous operations, such as sensor monitoring, actuator controlling, and robotic arm movement, to ensure that the components worked cohesively.

System Evaluation

The IoT-based smart laboratory system was evaluated through a series of performance tests to validate its functionality, efficiency, and reliability. The DHT11 sensor consistently recorded temperature and humidity values, and the TSL2561 luminosity sensor reliably measured light intensity levels. These sensor readings initiated appropriate actuator responses, including the automatic activation of the DC fan for ventilation when the temperature exceeded the preset threshold and the adjustment of light levels based on real-time luminosity data. The robotic arm demonstrated stability and precision, with effective coordination among the servo motors to perform complex movements, including rotating and adjusting positions to handle the pipette and transfer liquids successfully.

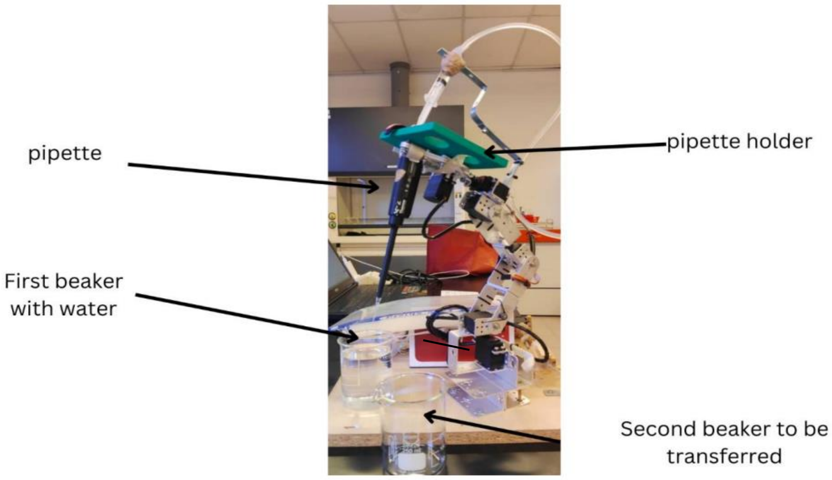
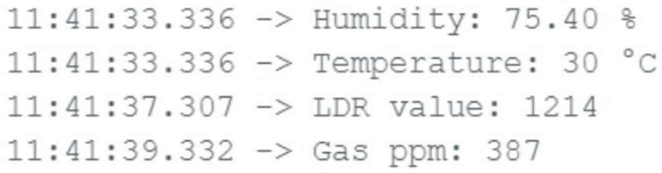


Fig. 2 Robotic arm setup demonstrating the pipetting operation

Sensor data were transmitted via the ESP-WROOM-32 microcontroller to the cloud server, where they were stored in a mySQL database and displayed on a user-friendly mobile application for real-time monitoring. The integration of the Blynk IoT platform enabled seamless remote control and monitoring, providing real-time feedback with minimal latency.



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11:41:33.336 -> Humidity: 75.40 %
11:41:33.336 -> Temperature: 30 °C
11:41:37.307 -> LDR value: 1214
11:41:39.332 -> Gas ppm: 387
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Fig. 3 Sample sensor readings displayed in the serial monitor

Figure 3 illustrates the real-time sensor readings captured by the system. The data includes humidity, temperature, light intensity, and gas concentration, demonstrating the system's capability to accurately collect and display environmental parameters for laboratory operations.

Fig. 4 Graphical interface of the Blynk application displaying real-time readings

The results of the IoT-based smart laboratory system indicate significant advancements in laboratory automation and safety. The integration of a robotic arm for pipetting tasks demonstrated high precision and reliability, reducing manual intervention and potential risks to laboratory personnel. By incorporating a sixth servo motor for hydraulic actuation, the robotic arm effectively simulated human-like pipetting, achieving liquid transfer. This highlights the potential for such systems to streamline repetitive laboratory tasks while maintaining consistency.

The system's environmental monitoring capabilities, enabled by sensors such as the DHT22, MQ-2, and LDR, ensured real-time responsiveness to changes in laboratory conditions. The automated activation of actuators, including fans, LEDs, and alarms, underscored the effectiveness of the IoT-enabled feedback loop in maintaining safety and operational efficiency. Furthermore, the Blynk application provided a user-friendly interface for remote monitoring and control, significantly enhancing the flexibility and usability of the system.

Challenges encountered during the development process included calibrating the sensors for optimal accuracy and ensuring the robotic arm's stability under varying load conditions. These challenges were addressed through iterative testing and refinement, demonstrating the system's robustness and adaptability. The use of an external power source and efficient power management strategies contributed to the system's energy efficiency, aligning with sustainability goals.

The modular design of the system facilitates scalability and customization for a wide range of laboratory applications, from routine liquid handling to hazardous material monitoring. However, future work could focus on further enhancing the robotic arm's functionality, incorporating advanced analytics and machine learning for predictive maintenance, and expanding the system to support more complex laboratory workflows.

CONCLUSION

The IoT-based smart laboratory system successfully integrates robotic automation, environmental monitoring, and real-time control to address key challenges in modern laboratory settings. The system's ability to perform precise pipetting, monitor environmental conditions, and respond dynamically to changing laboratory environments validates its potential as a reliable and efficient solution. By leveraging IoT technologies, the system minimizes human intervention, enhances safety, and improves operational efficiency.

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