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Intelligent Multi-Modal Lab Automation System with Advanced IoT Integration

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***Abstract*—** Laboratories in educational and research institutions require efficient management of resources, energy, access, and user information. Conventional approaches often depend on manual attendance, manual enquiry about available components, and aggregate energy measurements that do not provide sufficient visibility into individual laboratory loads. This work presents an Intelligent Multi-Modal Lab Automation System that addresses these requirements through three complementary modules: a rule-based laboratory chatbot, an IoT-based Energy Management System (EMS), and a face-recognition-based Attendance Management System (AMS) with access control and intruder detection. The chatbot is implemented using HTML, CSS, and JavaScript and uses Levenshtein distance for error-tolerant matching of laboratory and component names. It provides information about laboratories and the components available in them and is deployed as a web application. The EMS uses a PZEM-004T power sensor and NodeMCU to acquire voltage, current, power, energy, frequency, and power factor and transmit the measurements to a Blynk IoT dashboard. The AMS uses two USB cameras connected to a Raspberry Pi 5, face recognition, an SG90 servo motor for door control, Google Sheets for attendance storage, and an infrared sensor with Flask-based alert mechanisms for intruder detection. Alternative face-recognition approaches using YOLOv8 and ArcFace were evaluated during development; their real-time performance on the Raspberry Pi 5 was insufficient for the final implementation. The completed system demonstrates the feasibility of combining software assistance, energy monitoring, and security-oriented automation to improve laboratory operation, resource accessibility, and accountability.

Keywords: Laboratory Automation, Internet of Things, Energy Management System, Face Recognition, Attendance Management, Rule-Based Chatbot.

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I. INTRODUCTION

A laboratory is an important environment for experimental research, practical learning, and project development. As the number of users, laboratory resources, and equipment increases, manual methods for resource enquiry, energy monitoring, and attendance management become less convenient. The proposed work was motivated by the need to automate routine laboratory activities while retaining a simple and practical architecture. The system therefore focuses on three operational areas: resource assistance through a chatbot, equipment-level energy monitoring, and automated attendance with access control.

The first module provides a digital interface through which students and teachers can identify laboratories and determine the components available in a selected laboratory. The chatbot follows a rule-based approach because the scope of interaction is limited and the expected answers are predefined. Levenshtein distance is incorporated to tolerate minor spelling errors, thereby reducing dependence on exact input strings.

The second module provides equipment-level energy visibility. Instead of relying only on an overall energy meter, the proposed EMS measures the electrical parameters associated with a selected load. The PZEM-004T sensor sends measurements to a NodeMCU controller, which transmits them through Wi-Fi to a Blynk dashboard. The resulting dashboard provides real-time visibility into voltage, current, power, energy, frequency, and power factor.

The third module addresses laboratory security and accountability. Two USB cameras are used for entry and exit, while a Raspberry Pi 5 performs image processing, face recognition, attendance logging, and servo control. Recognized users can activate the door mechanism, while attendance information is stored in Google Sheets. An infrared sensor is also used to detect movement when no authorized person is recorded inside the laboratory, triggering email and call alerts through Flask-based APIs.

A. Objectives

• To implement a front-end-based chatbot that provides timely information about laboratory resources and reduces resource accessibility issues.

• To implement an Energy Management System for monitoring laboratory equipment and presenting the energy measurements through an analysis dashboard.

• To implement face-recognition-based access control and attendance management to improve laboratory security and accountability.

II. Related Work

Existing research demonstrates the use of chatbots, IoT-based energy meters, and automated attendance systems as separate solutions. Studies on chatbots have investigated rule-based keyword matching as well as machine-learning and Natural Language Processing (NLP) approaches. Pavitha et al. reported a multipurpose chatbot using cosine similarity, with an accuracy of 93% [9]. Nithuna and Laseena reviewed rule-based and machine-learning-based chatbot implementations [8]. Educational chatbot studies have also explored the use of structured datasets, graphical interfaces, and supervised learning to support students [10].

IoT-based energy monitoring research has demonstrated the advantages of real-time sensing and cloud-based visualization. Barman et al. described an IoT-based smart energy meter using an ESP8266 for real-time monitoring and cloud transmission [3]. Other studies have combined NodeMCU, power sensors, cloud dashboards, forecasting, alerts, and automated appliance control [6,7]. Comparative studies involving IoT platforms such as Web, ThingSpeak, and Blynk have demonstrated the suitability of Blynk for remote monitoring and implementation, although its operation depends on internet connectivity [2,11].

Automated attendance research has explored RFID, face recognition, and other biometric approaches [1,4,5,12]. Face-recognition systems based on EigenFaces, Fisherfaces, and Local Binary Patterns Histograms have been applied to automated attendance and access-control applications [1,5,12]. RFID systems can provide automated identification and login/logout recording, but they depend on physical cards [4]. Face recognition provides a contactless approach to automated attendance while also supporting real-time monitoring [1,5,12].

The reviewed studies provided the technical direction for the present system. The distinguishing feature of the proposed work is the combination of laboratory resource assistance, equipment-level energy monitoring, and face-recognition-based security within a single laboratory-oriented automation system.

III. Proposed Multi-Modal System

The proposed system consists of three modules that address different operational requirements of a laboratory. The chatbot is implemented as a lightweight web application, the EMS combines electrical sensing with cloud visualization, and the AMS combines computer vision, embedded control, cloud storage, and security alerts. The modules are functionally distinct so that each can operate according to its own requirements while contributing to the overall objective of laboratory automation.

A. Laboratory Chatbot

The chatbot is designed for a limited and well-defined conversational domain. A reverse lookup structure is used to map components to laboratories. When a user enters a laboratory or component name, the input is compared with the predefined entries. Minor spelling errors are handled through Levenshtein distance, which evaluates the minimum number of insertion, deletion, and substitution operations required to transform one string into another. A configurable threshold determines how tolerant the matching process is.

The user interface is developed using HyperText Markup Language (HTML), Cascading Style Sheets (CSS), and JavaScript. HTML provides the page structure, CSS controls the visual presentation and layout, and JavaScript implements the interaction logic. Search results are presented in a consistent format, with laboratory information arranged for readability. If the entered value cannot be matched sufficiently, related names are suggested so that the user can retry the query.

The completed front-end application is deployed using Netlify. The source code can be maintained through a GitHub repository and connected to the hosting platform, allowing the chatbot to be accessed through a web link on supported devices. Testing demonstrated that the rule-based design provides predictable outputs for the predefined laboratory queries and makes functional errors easier to identify.

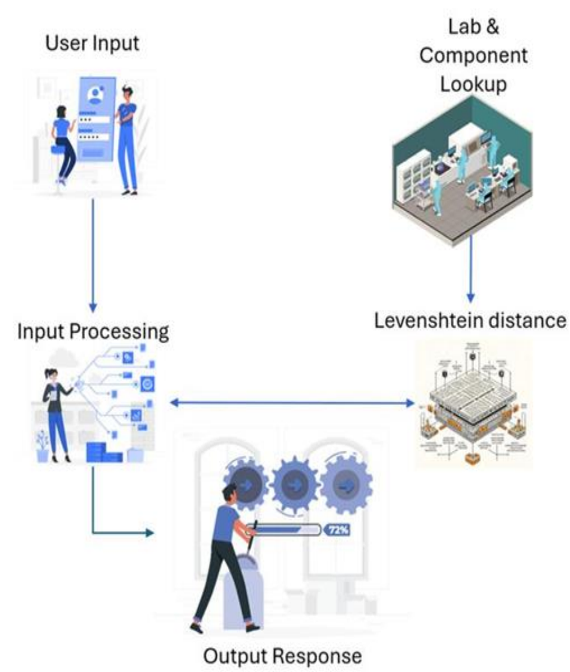

Figure 1: Block diagram of Chatbot

B. Energy Management System

The EMS is designed to measure the electrical characteristics of an individual load rather than only the aggregate consumption of a room. A PZEM-004T-10A module measures AC voltage, current, power, energy, frequency, and power factor. The measured information is transmitted to a NodeMCU controller, where it is processed and prepared for cloud transmission.

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The NodeMCU provides Wi-Fi connectivity between the sensing layer and the cloud dashboard. Blynk IoT is used for visualization and remote monitoring. Virtual pins are assigned to the measured parameters, with the dashboard providing separate fields for voltage, power, energy, current, frequency, and power factor. Gauge and graph widgets allow both instantaneous values and trends to be observed. The dashboard also displays the most recent update information, which helps distinguish current data from cached values when connectivity is interrupted.

The operational sequence is therefore: electrical measurement by the PZEM-004T, digital acquisition by NodeMCU, formatting and transmission through Wi-Fi, and visualization through Blynk. The prototype was tested with a load, and the measured values were observed both through the Arduino development environment and the Blynk dashboard. The system demonstrated that individual sections or devices can be monitored instead of relying only on an overall room-level measurement.

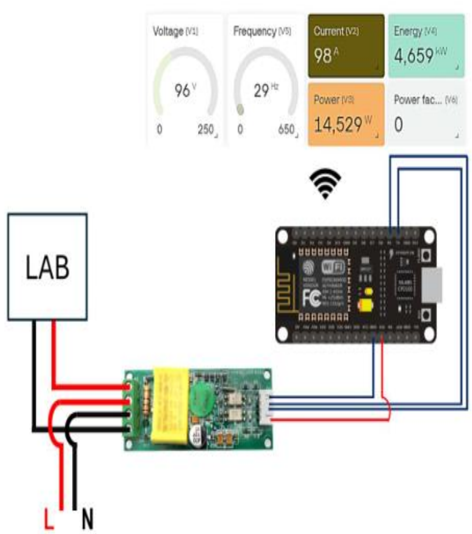

Figure 2: Block diagram of Energy Management System

C. Attendance, Access Control, and Intruder Detection

The AMS is centered on a Raspberry Pi 5. Two USB cameras are used simultaneously, with one positioned at the entry and the other at the exit. The cameras provide continuous frames to the recognition system. When an authorized face is recognized, the corresponding entry or exit event is recorded and the access-control mechanism is activated.

An SG90 servo motor controls the door latch. After successful recognition, the servo rotates to open the latch for a predefined interval and then returns to the locked position. The design also supports supervised student access: a student can enter when an authorized person is present and provides the required access through face recognition.

Attendance events are stored in Google Sheets. Because a user may enter and exit multiple times during a day, every individual event can be recorded while a separate attendance record retains the first login and last logout for the day. This provides a practical representation of the person's overall laboratory presence.

Security is extended through an infrared sensor and Flask-based alert APIs. If the system records zero authorized people inside the laboratory but detects movement, the event is treated as a possible intrusion. An email and a call alert are then sent to authorized personnel. This provides a second layer of protection beyond face recognition.

IV. Attendance Management System Implementation and Algorithm Evaluation

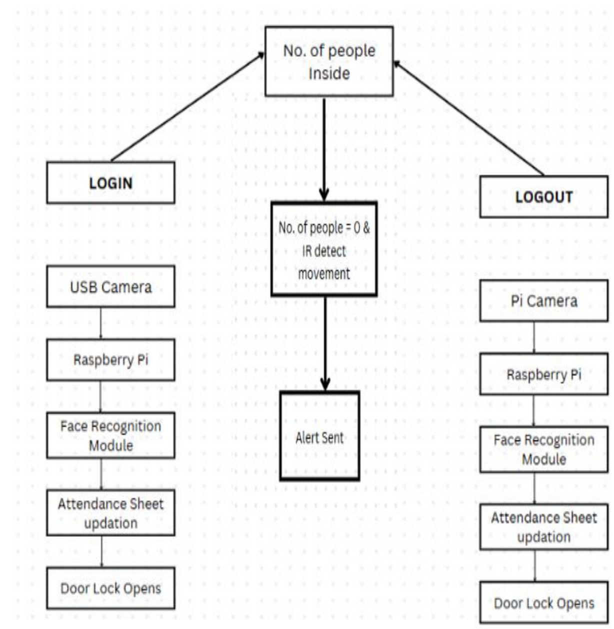

Figure 3: Block Diagram for Attendance Management System

A. Face Recognition-Based Attendance and Access Control

The Attendance Management System (AMS) was developed to automate laboratory attendance while improving access control and security. Unlike conventional systems that rely on manual recording of entry and exit times, the proposed system uses face recognition to automatically identify authorized users and record their attendance. The main computational unit of the system is a Raspberry Pi 5, which is connected to two USB cameras. One camera is positioned at the entrance and the other at the exit of the laboratory. The two cameras operate as separate processes, and their combined operation provides complete entry and exit tracking.

The face recognition pipeline used in the final implementation is based on Histogram of Oriented Gradients (HOG) and the project's Schrödinger-equation-based image enhancement approach. The Raspberry Pi 5 performs image processing and recognition operations and coordinates the other components of the system. When an authorized face is recognized, the corresponding entry or exit event is recorded automatically.

An SG90 servo motor is used for physical access control. When an authorized person is recognized, the servo motor rotates to open the door latch. The door remains open for a predefined duration, after which the servo returns to its original position and automatically locks the door. This prevents unauthorized access when an authorized person is not available.

The system also supports controlled access for students. A student can enter the laboratory when an authorized person is present and performs the required face-recognition-based access. Thus, access to the laboratory is controlled by the presence and authentication of an authorized person.

B. Attendance Recording and Cloud Integration

Attendance information is automatically updated in Google Sheets. Every entry and exit event is recorded, allowing multiple entry and exit events to be maintained for the same person during a day. This is useful when a person leaves and subsequently re-enters the laboratory.

For final attendance calculation, a separate attendance record is maintained using the first login and last logout of each person. This provides a simplified daily attendance record while retaining the detailed entry and exit information separately. The use of automated cloud-based recording also reduces manual entry errors and eliminates the need for a dedicated person to maintain attendance records.

The attendance data stored in Google Sheets can be accessed online and can also be downloaded for offline use. This provides convenient access to the recorded attendance information and reduces the possibility of manual manipulation of attendance records.

C. Intruder Detection and Alert Mechanism

In addition to attendance and access control, an intruder detection mechanism was incorporated to improve laboratory security. An infrared (IR) sensor is used to detect movement inside the laboratory. The number of authorized people inside the laboratory is determined from the entry and exit information recorded by the system.

If the system detects movement inside the laboratory while the recorded number of authorized people is zero, the condition is considered a possible intrusion. Flask-based APIs are used to generate alerts, through which an email and a call alert are sent to the authorized personnel. This additional security mechanism helps protect laboratory equipment and components when no authorized person is present.

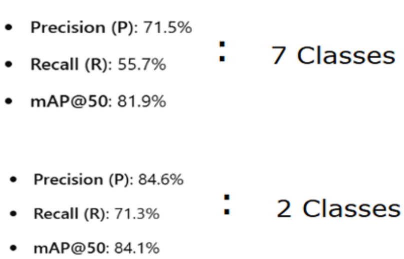

Figure 4: Performance Evaluation for Yolo v8

D. Face Recognition Algorithm Selection

During development, YOLOv8 and ArcFace were also evaluated as alternative face-recognition approaches. YOLOv8 was trained using seven-class and two-class configurations, while ArcFace was trained using approximately 600 images for two classes. Although the models showed useful training results, they did not provide sufficiently reliable performance during real-time testing using the USB cameras and Raspberry Pi 5.

Therefore, the HOG and Schrödinger-equation-based approach was selected for the final implementation based on its suitability for the target hardware and real-time operation.

V. RESULTS AND DISCUSSION

The proposed multi-modal laboratory automation system was implemented and evaluated through its three major modules: the laboratory chatbot, Energy Management System, and Attendance Management System. The results demonstrate the feasibility of integrating web technologies, IoT hardware, cloud services, computer vision, and physical access control into a laboratory automation system.

A. Chatbot Results

The rule-based chatbot successfully provided information regarding laboratory locations and the components available in each laboratory. The use of Levenshtein distance allowed the system to tolerate minor spelling errors in laboratory and component names. When an input could not be matched sufficiently, related names could be suggested to the user.

The chatbot was developed using HTML, CSS, and JavaScript and deployed as a web application. Its front-end architecture allows users to access the system through a web link on different devices. The rule-based approach also provides predictable outputs and makes errors in the predefined query-response system easier to identify during testing.

Figure 5: Chatbot initial display

B. Energy Management System Results

The IoT-based Energy Management System successfully acquired electrical parameters from the PZEM-004T sensor and transmitted the measurements through the NodeMCU to the Blynk IoT platform. The system monitored parameters including voltage, current, power, energy, frequency, and power factor.

The measurements were displayed through the Blynk dashboard using dedicated widgets and graphs. During testing, the voltage and other measured parameters remained consistent for the tested load condition. The system therefore demonstrated the feasibility of monitoring an individual laboratory load remotely rather than depending only on overall laboratory-level energy measurements

The cloud dashboard also provides a basis for future analysis of energy-consumption trends and estimated cost. Since the measurements can be viewed remotely, the system enables monitoring without requiring the user to remain physically near the laboratory equipment.

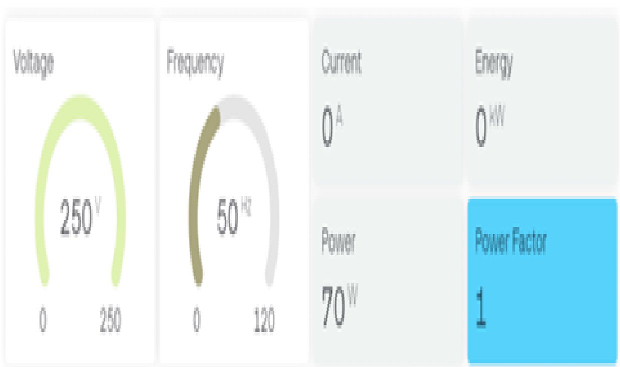

Figure 6: Output of EMS in Blynk IoT

C. Attendance Management System Results

The final Attendance Management System integrated two USB cameras, Raspberry Pi 5, an SG90 servo motor, Google Sheets, and an IR-based intruder detection mechanism.

The entry and exit cameras operated as separate processes to capture the movement of users. When an authorized face was recognized, the system recorded the event in Google Sheets and activated the servo motor to open the door latch. The servo subsequently returned to its locked position after the predefined open duration.

The system supported multiple entry and exit events for the same person during a day. These events were retained in the detailed attendance records, while a separate attendance record calculated the first login and last logout for final daily attendance. This approach provides both detailed movement information and a simplified daily attendance record.

The access-control mechanism also supports supervised student entry. A student can access the laboratory when an authorized person is present and performs the required face-recognition-based access. This reduces the possibility of unauthorized access while allowing legitimate laboratory usage.

The intruder detection mechanism further strengthened laboratory security. When movement was detected by the IR sensor while the system indicated that no authorized person was inside the laboratory, the condition was identified as a possible intrusion. During testing, the system generated both email and call alerts to the authorized person. This provides an additional mechanism for detecting unauthorized activity and protecting laboratory components.

The evaluation of YOLOv8 and ArcFace during development showed that training performance alone is not sufficient when selecting a model for an embedded real-time application. Both alternatives were tested on the Raspberry Pi 5 but were not selected for the final implementation. The HOG and Schrödinger-equation-based approach was therefore retained for the final hardware system.

VI. Conclusion

The three modules address different but complementary laboratory-management requirements. The chatbot improves accessibility to laboratory information, the EMS provides visibility into equipment-level energy consumption, and the AMS improves attendance tracking, physical access control, and laboratory security.

The modular architecture provides flexibility because each subsystem can perform its intended function independently. At the same time, their combined implementation demonstrates how software applications, IoT devices, cloud platforms, embedded computing, computer vision, and physical actuators can be integrated into a practical laboratory automation solution.

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