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Exploring IIoT: Wireless Control Systems with ESP8266 as a Web-ServerController— Basic Experimentation

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Abstract This research presents the design and implementation of a low-cost, modular Industrial Internet of Things training kit aimed at enhancing hands-on IIoT education in academic and experimental settings. The primary goal was to bridge the gap between theoretical learning and practical industrial automation through the development of a WiFi-enabled educational trainer based on the ESP8266 microcontroller. The system integrated DC and AC loads to simulate real-world electromechanical components commonly found in flexible manufacturing systems and computer integrated manufacturing. A web-based graphical user interface was developed using HTML, CSS and C++ within the Arduino IDE, facilitates wireless control. Seven different basic and fundamental experiments were conducted focusing on hardware architecture, device interfacing, wireless communication, and internet network connectivity. Results demonstrated effective control of resistor connected LED, DC, and three-phase AC loads, with a control response time of less than 250±2 ms and a wireless range up to approximately 30±2 meters. The uniqueness of the work is its scalable design that is accessible and IIoT literate, particularly in the developing countries, such as Pakistan. Although the limitations are limited to basic analytics and absence of encryption, the limitations are to be improved eventually. The kit provides a viable basis of IIoT skill building and helps in smart manufacturing projects that are in line with Industry 4.0.

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1 Introduction

Industrial Internet of Things (IIoT) is a fundamental change in the sphere of industrial automation, which is utilizing the new digital technologies to improve the efficiency of operations, their productivity, and the safety of workplaces [1–4].

IIoT, as the extension of the more general notion of the Internet of Things (IoT), introduces the idea of connectivity and intelligence to the industrial machines, processes, and systems, which leads to a new era of data-driven decision-making and transparency of operations[5–9]. A number of converging technological trends have triggered the development of IIoT.

Since the late 20 th century, the proliferation of sensors, actuators, and programmable logic controllers (PLCs) provided the basis of real-time monitoring and control of industrial assets [10, 11]. At the same time, the development of communication standards and networking protocols allowed to integrate the system smoothly, exchange data and monitor it remotely in real-time, and do all of that smoothly and without any problems in the hardware integration process [12, 13].

The core aspect of Industry 4.0 is the combination of cyber-physical systems, cloud computing, and smart analytics. The focus of this vision is on called "smart factories" that have autonomous and interconnected devices able to gather, analyze, and react to data in real-time to increase productivity and flexibility throughout the value chain [14, 15].

The wireless communication is central in the achievement of this vision because it provides immense benefits over the wired systems in terms of scalability, flexibility and cost-effectiveness. More specifically, the WiFi technology has also become a standard of choice when the IIoT applications require a high data rate, high-performance, and a wide range of compatibility with devices.

The ESP8266, created by Espressif Systems, has received considerable popularity among microcontrollers which operate on WiFi because of its small size, low cost, and the fact that WiFi is built-in features. The ESP8266 is based on IEEE 802.11 b/g/n standards and has the ability to work in both infrastructure and peer-to-peer (P2P) networking modes [16, 17]. It can be used in battery-powered industrial applications due to its low power consumption and sophisticated sleep modes, whereas it can be easily integrated with a wide range of sensors and actuators through its flexible peripheral interfaces [18, 19].

The proposed research focuses on investigating and discussing the applicability of ESP8266 microcontroller in the design of wireless control systems to implement simple IIoT projects. This paper aims at developing a testbed based on the ESP8266 as a web-based controller of basic industrial processes. The objectives of this study are specific as they involve exploring the features of the ESP8266 as a tool of wireless communication and control within industrial applications; Design and development of a working experiment using ESP8266 as a web server to perform industrial automation tasks; Testing the performance, reliability and scalability of the proposed system in real-life scenarios; Uncovering issues and constraints of implementing ESP8266-based control systems within industrial environments and establishing practical solutions to counter them.

The proposed study aims to come up with easy and practical control interfaces in industrial applications by combining the WiFi of the ESP8266 and the modern web technologies . The knowledge acquired during the research should be relevant to the existing body of knowledge in the IIoT systems design and lead to the increased utilization of wireless control technologies in industrial processes.

2 Literature Review

2.1 Emergence of IIoT in Industrial Automation

The Industrial Internet of Things (IIoT) is an emerging disruptive technology in industrial automation, which has received considerable attention in recent years. Its ability to transform the conventional production methods and improve the efficiency of operations has been a well-recognized fact of both scholarly literature and industry publications. With the increasing interconnections of manufacturing systems, IIoT allows making real-time monitoring, predictive maintenance, and automated decision-making. The IIoT is based on the theoretical base of Industry 4.0, which denotes the integration of digital and industrial systems. Researchers point out that Industry 4.0 is focused on cyber-physical systems that combine sensors, software, and communication technologies to communicate with the physical environment with the help of these systems [20–24]. The necessity of interoperability and data analytics in real time is also emphasized by scholars to allow smart factories and intelligent production lines to work with the goal of enabling them in the future [25–27]. The IIoT adoption opens the way to tailor-made production, optimization of resources, and the global market competitiveness. In addition, it is sustainability-friendly as it lowers wastage and the use of energy consumption is reduced [28–30].

2.2 Wireless Communication and Smart Manufacturing

Wireless communication is quite essential in facilitating the vision of Industry 4.0, as it will give the interconnected industrial devices the backbone of connectivity. Even in the absence of a strong communication infrastructure, it would be either ineffective or impossible to exchange data between cyber-physical systems and control centers. Such technologies as the WiFi, Bluetooth, ZigBee, and LoRa have been discussed in terms of their applicability in the industry setting [31–33]. Researchers underline the benefits of the WiFi in intelligent manufacturing facilities, especially its high data rates, ubiquity, and compatibility with the current network facilities [34–37]. Wireless technologies enable real-time data collection and monitoring resulting in enhanced responsiveness and agility of operations [38, 39]. Moreover, wireless systems are much simpler and cheaper than the wired infrastructure. Recent research also shows that the flexibility to WiFi will be used in the future of automation in the industrial system, particularly in the flexible manufacturing configurations and mobile robotics systems as industrial systems become increasingly sophisticated and dynamic over time [40–44].

2.3 WiFi Technology and ESP8266 in IIoT Systems

WiFi is one of the wireless technologies that have become popular in the industrial world as it has become dependable, fast and has a high data transfer rate and is compatible with many other technologies. When comparing WiFi to other protocols in a comparative study, WiFi is always indicated as a better protocol in latency, bandwidth, and compatibility between devices on interoperability characteristics of WiFi and other protocols [45–47]. ESP8266 microcontroller, which is invented by Espressif Systems, has become popular as a universal IIoT platform. It integrates processing power and inbuilt WiFi that provides smooth communication with the cloud systems and remote servers. Researchers have investigated the ESP8266 capability to communicate with different sensors and actuators and showed that the ESP8266 is appropriate in real-time industrial control systems [48–50]. It is very cheap and low-power consumptive and hence ideal in educational and experimental IIoT configurations. ESP8266 has been applied in energy monitoring, machine condition diagnostics, and environment sensing in industrial prototypes, and along with other applications, it is used in smart grids and smart cities to do the previously mentioned applications and more [51, 52]. The accumulating literature proves that ESP8266 can be effectively used as the solution to small to medium-scale IIoT implementations [53–55].

2.4 Web Technologies for IIoT Control Interfaces

The integration of ESP8266 microcontroller with technologies such as web technology adds to its utility in the industrial field. By setting up the ESP8266 as a web server, easy-to-use interfaces can be created with the help of the programming languages like HTML, CSS and JavaScript, by which operators can remotely control and monitor processes. Researchers in recent studies created applications where users could switch relays on and off and see sensor data and adjust settings using web dashboards [56–58]. Such interfaces make software more accessible and require less so-called "specialized" software to be used, which democratizes IIoT adoption. Moreover, the use of the protocols for the internet of things (IoT) namely the protocols for the representation of a resource (RESTful API), and the use of message queuing transferable messages (Mosquitto MQTT), with ESP8266 web servers, allows the seamless integration with industrial cloud services and dashboards [59, 60]. These are all features that offer data visualization, alert notifications, and control anywhere with the help of smartphones or computers. The ease of set up and rapid prototyping capability has also encouraged its use in academic institutions [61–64].

2.5 Security and Reliability Challenges in IIoT

Despite its promise, there are challenges to the deployment of wireless control systems in industrial environments regarding reliability, security, and interoperability. Wireless networks are also inherently more prone to interference, signal loss, and cyber threats. Recent literature identifies risks like denial of service (DoS) attacks, man-in-the-middle (MITM) vulnerabilities and unauthorized access in IIoT systems [64, 65]. These challenges require strong encryption protocols, user authentication methods, and secure firmware updates. Researchers also highlight the importance of fault-tolerant communication protocols and redundancy to keep working in the event of link failures [66–68]. Furthermore, data integrity and confidentiality are important, particularly when important processes are monitored or controlled remotely [69, 70]. Future research is aimed at the development of light-weight security frameworks for the limited resources of microcontrollers such as ESP8266 [71–74].

2.6 Comparative Analysis of Wireless Protocols in IIoT

In the current landscape of Industrial Internet of Things (IIoT) applications, a number of wireless technologies are available with different advantages to meet different industrial needs. While we use WiFi and ESP8266 module in this study because of their accessibility and affordability in educational environments, there are other technologies that can be considered to build IIoT systems such as LoRa and ZigBee which can be interesting to use. LoRa is great for long-range, low-power communication applications, which makes them ideal for large industrial fields or remote monitoring applications [75, 76]. ZigBee on the other hand supports strong mesh networking that boosts reliability in dense device environments. Studies show that hybrid solutions of WiFi and LoRa or ZigBee enhance scalability and fault tolerance [77–80]. Acknowledging these options to contextualize the place of WiFi in IIoT and explore the protocol diversity in the trainer kit designs going forward [81, 82].

3 Methodology

3.1 Literature-Guided Experimental Foundation

Before doing our experimental work to understand the architecture of IIoT, we mainly read extensively different research articles that are part of our literature study. Our research consisted of four basic experiments to investigate electronic and electro-mechanical devices, such as a resistive and inductive load, an embedded controller, various connectivity types, cloud integration and industrial applications. These experiments formed the basis for the creation of an educational IIoT trainer, which gathered the knowledge from our practical activities. Our industrial application tests started with connection of resistive or inductive DC/AC loads to their respective electrical or electromechanical drivers. These drivers were then interfaced with the output of a WiFi-enabled System on Chip (SoC) ESP8266 controller.

For the purpose of user interaction, we built a web-assisted graphical user interface (GUI) with the help of the programming language (html), which is nicely coupled with the C++ program with the open source Arduino IDE editor. The procedure steps involved in conducting experiments on industrial Internet of Things using our IIoT trainer can be seen by the examples in Figure 1. Based on our literature review, it was realized that the recent development of embedded controllers such as an ESP8266 integrated circuit has become a crucial fundamental tool to teach IIoT education and skills to academics. This preference is attributed to a number of factors including affordability, abundance in the local marketplace, reliability and the availability of open source code resources. The adoption of the WiFi protocol is based on the imperative need of wireless connectivity, the prerequisite to comply with the standards of Industry 4.0 in all smart manufacturing industries.

3.2 ESP8266 Integration and GUI Implementation

The ESP8266 is the core element in the IIoT trainer kit and is a versatile, accessible and low-cost IIoT electronic controller. Widely available in local markets, its user-friendly nature makes it the perfect choice for this research endeavor. With its built-in WiFi capabilities, it is a clear implementation of wireless connectivity with web clients, especially with web graphical user interfaces. Google Chrome has been chosen as the main web browser due to compatibility and reliability on it during the experimentation process. An IIoT training kit gives a physical foundation for learning components in real-world Flexible Manufacturing Systems (FMS) and Computer Integrated Manufacturing Systems (CIM). The LED load can be used to represent status indicators or warning lights often found in FMS and CIM systems.

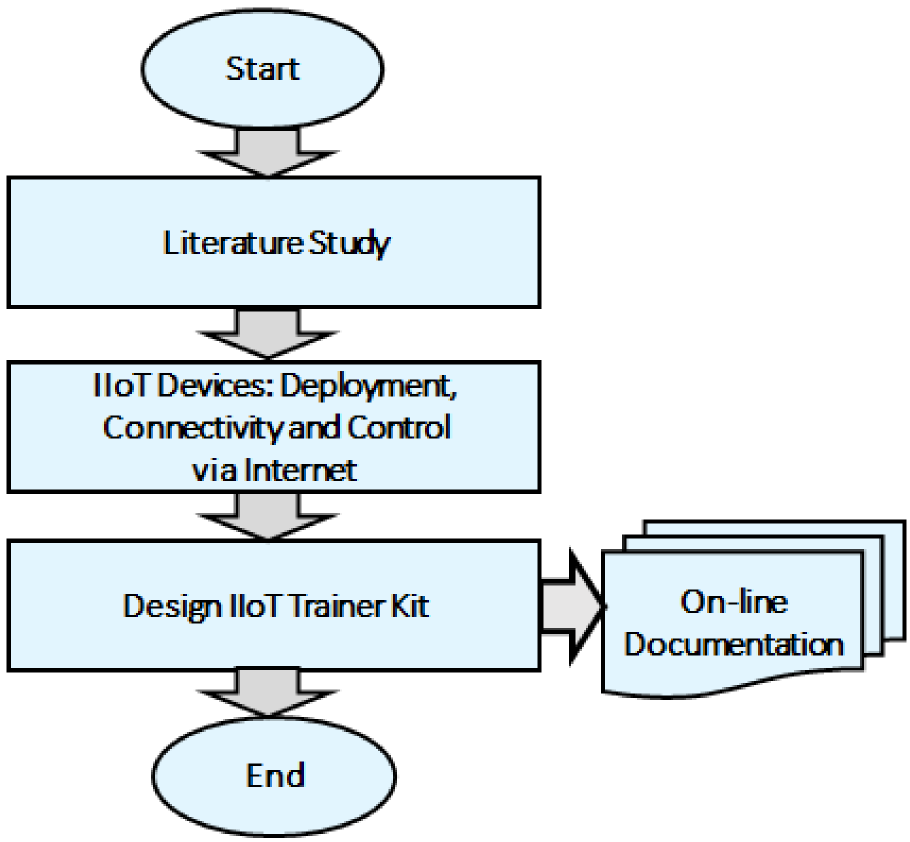

Figure 1. Procedural steps involved in conducting experiments on the industrial Internet of Things using our IIoT trainer.

3.3 Industrial Load Simulation through IIoT Kit

In the real world, LED indicators give immediate visual feedback on the status of equipment, line health, or production stage to assist operators in monitoring and troubleshooting equipment in real-time. In an FMS configuration, Light Emitting Diodes (LEDs) can be used to provide feedback on the status of robotic arms or for quality control alerts in assembly lines. The DC load in our setup can simulate something as small as a conveyor, fan or actuator, which are ubiquitous in manufacturing systems used to move or control the air circulation in automated assembly processes. In FMS and CIM, there are various DC loads for certain functions in the production process, i.e. automated positioning, transport or climate control for sensitive manufacturing environments. The capability to monitor and control DC loads remotely is consistent with the role the IIoT plays in predictive maintenance and efficient resource management.

3.4 Realistic Replication of Industrial Environments

The three-phase motor is used to represent industrial grade machinery in FMS and CIM systems, where motors are used to power critical equipment such as pumps, compressors, and large conveyors. In a flexible manufacturing system, three-phase motors are used for heavy duty applications requiring high torque and efficiency based on production. Within a CIM setup, these motors can be incorporated into robotic arms or automated tool changers, to increase automation and to limit the need for manual interventions. These aspects are very important in teaching real world dynamics to students. The use of a trainer kit with such a wide load compatibility allows the learners to gain practical experience with different types of machinery in a controlled environment.

3.5 Identified Limitations and Opportunities for Enhancement

Distributed nodes, dependency on the internet, lack of discussion on security, lack of data analytics are some of the limitations that were noted in the present research work, as shown in Figure 2. These constraints show the need for more advanced features, such as edge computing, real-time analytics, and secure communication protocols in future versions of the IIoT trainer. Future work can also explore incorporating other types of wireless protocols such as LoRa or 5G, particularly to simulate more demanding industrial setups. Improving the modularity of the trainer kit can offer scalability and the capacity to add more sensors and actuators. Overall, while this research opens the doors for IIoT experimentation in the academic realm, constant improvements will ensure that these are aligned with industrial trends and educational requirements.

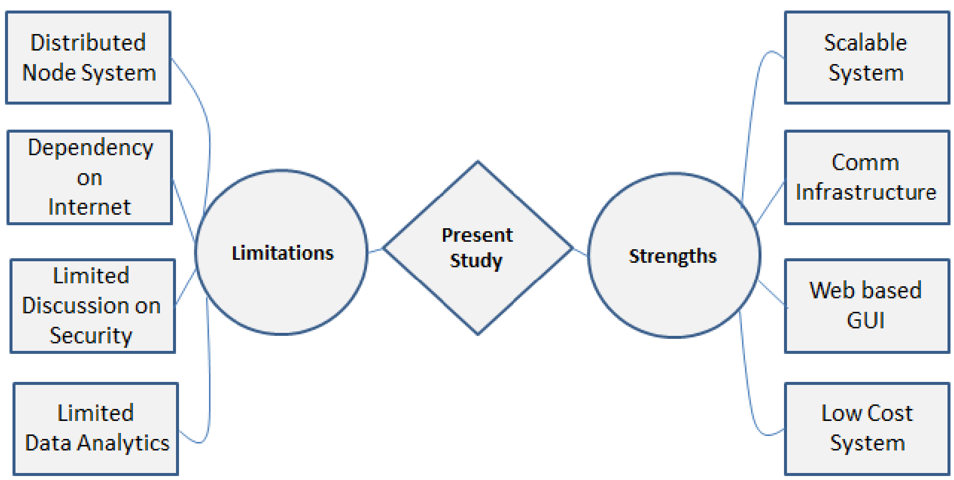

Figure 2. Block diagram of limitations, present work and strengths of research work.

4 Results

4.1 Understanding Device

4.1.1 Experiment 1: Interfacing limiting resistor with LED as DC load

The initial experiment involved interfacing a light emitting diode (LED) with an ESP8266 embedded server using a limiting resistor. This allowed students to gain hands-on experience in making wire connections from the digital output pin of the ESP8266 integrated chip to the series connection of the limiting resistor with the LED. They were also introduced to the concept of current flow, wherein the pin of the ESP8266 acted as a high potential, passing through the series-connected devices and then to ground, representing low potential. Subsequently, a simple firmware was developed in the C++ language to control the flashing light of the LED. Figure 3 shows the schematic diagram of interfacing a limiting resistor with LED working as a DC load.

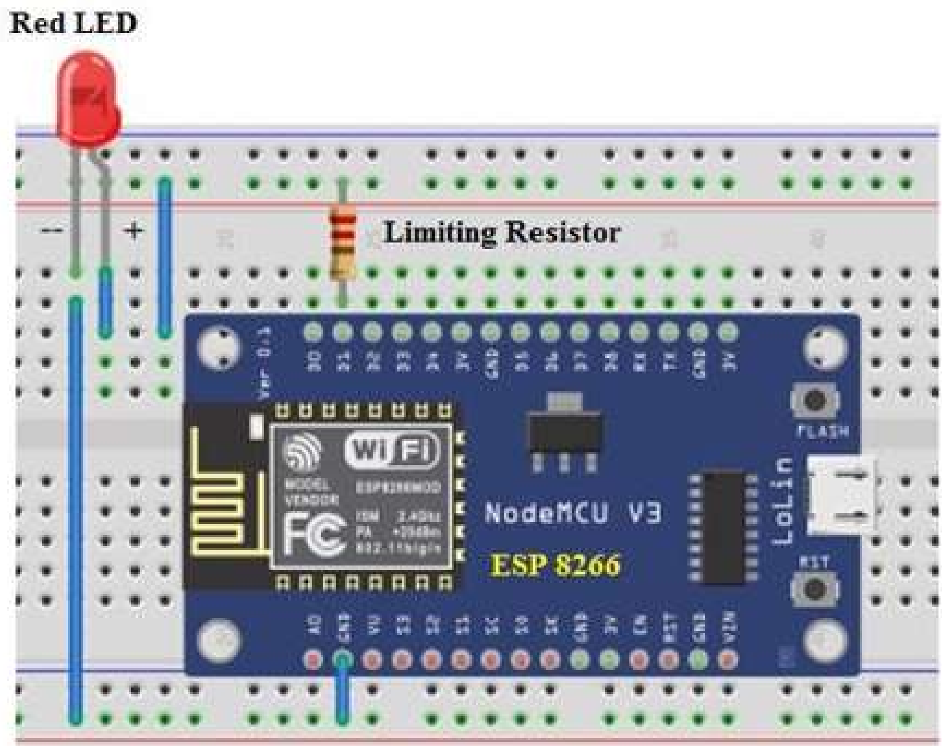

Figure 3. Schematic diagram of interfacing ESP8266 with resistor connected LED dc load.

4.1.2 Experiment 2:Interfacing of an electromagnetic relay as driver for AC load

The second experiment involved integrating an opto-coupler integrated electromechanical relay with the ESP8266 main controller as shown in Figure 4. An electromechanical relay is a magnetic device with normally open and normally closed contacts suitable for use with 220V AC loads. However, the ESP8266 controller cannot directly interface with a switching relay device due to the inductive properties of the relay module. To address this issue, an opto-coupler was introduced between the ESP8266 and the relay device to ensure proper functionality. A high pulse on the digital output of the ESP8266 can activate the normally open contact, effectively closing it to power the AC load. To safeguard the ESP8266 circuit, a rectifier diode can be connected in parallel in reverse bias with the relay. This configuration not only protects the ESP8266 but also enhances the understanding of students in controlling AC loads. Additionally, the relay can be utilized to control DC loads. Furthermore, the firmware programming was created, to ease the control of the 220V AC load, for a complete solution in interfacing the relay to ESP8266.

4.1.3 Experiment 3:Interfacing of variable frequency drive system as driver for AC load

In the third experiment shown in figure 5, we integrated a variable frequency drive (VFD) controller with a three-phase motor. To facilitate control, a small 5V DC relay was inserted between the ESP8266 and the VFD controller, enabling the motor to rotate in a forward direction (clockwise). VFDs are power electronics controllers designed to regulate various parameters such as acceleration, deceleration, torque, speed, and direction of three-phase

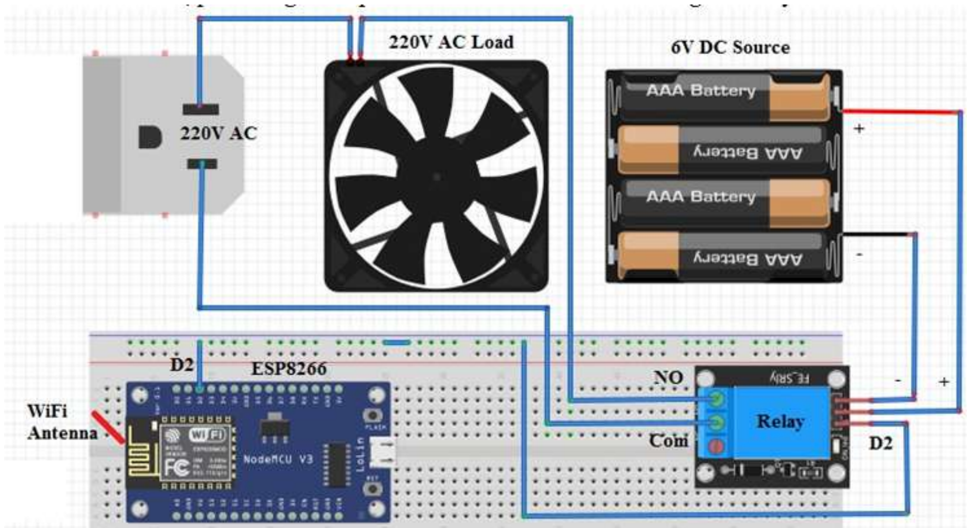

Figure 4. Schematic diagram of interfacing ESP8266 with ac fan.

motors. Initially, the VFD motor controller was configured and then linked to the three-phase motor. A simplified schematic diagram demonstrates the interconnection of the ESP8266, relay, VFD, and low horsepower three-phase motor. Through this experiment, students acquire hands-on experience in configuring industrial VFDs and understanding their integration with industrial three-phase motors, along with ESP8266-connected relays. Furthermore, a firmware was developed for the ESP8266 to enable automatic starting and stopping of the three-phase motor.

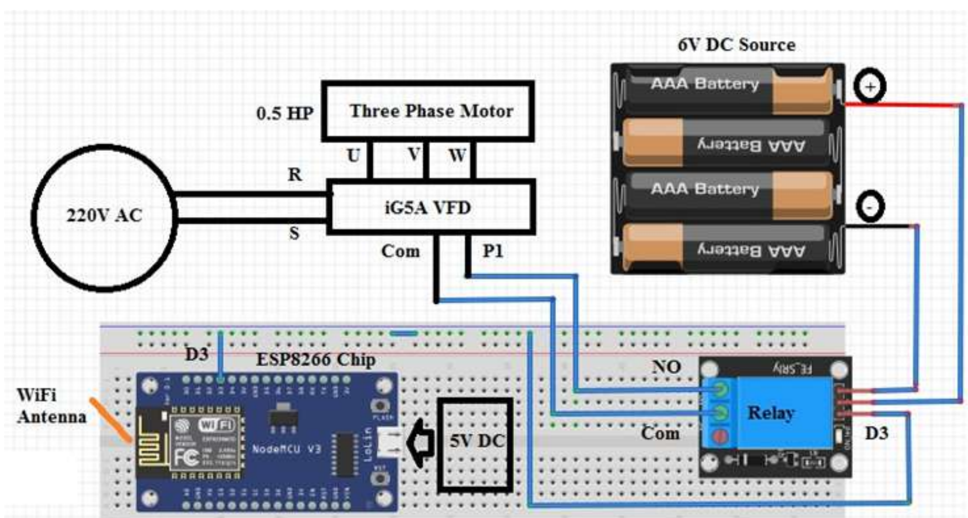

Figure 5. Schematic diagram of interfacing ESP8266 with VFD assisted three phase motor.

4.2 Understanding Connectivity with HTML Webpage

In this section, we established a connection between the embedded web-server ESP8266 and DC/AC loads, interfacing them with a laptop (acting as the web-client) via the WiFi IP address. The firmware was developed using ESP8266 code, HTML, and CSS. Upon execution, the ESP8266 web server displayed the IP address on the Arduino

IDE's serial monitor, which was then accessed via a Google web browser to obtain a graphical user interface for controlling the DC and AC loads. Through this process, various basic experiments were successfully conducted. Students gained hands-on experience in HTML programming and interfacing industrial hardware such as DC loads, single-phase AC loads, and three-phase AC loads with a web-client, leveraging Internet connectivity to establish the foundation for Industrial Internet of Things (IIoT) applications.

4.2.1 Experiment 4: Wireless digital control of dc load (LED) using web graphical user interface

The objective of this experiment was to achieve wireless LED control via a web-based graphical user interface accessible over the internet as shown in figure 6. The interface included buttons for turning the LED on, off, and a master control for overall operation, all designed within a web GUI. WiFi technology made the communication between the interface and the LED possible. An implementation of the web GUI was done by integrating the HTML and CSS coding into ESP8266 firmware. In this configuration, the ESP8266 acted as a web-server and the web GUI of a laptop acted as the web-client. This experiment was intended to acquaint the students with the firmware development for ESP8266 web-server and the process of generating an IP address for accessing the graphical user interface of ESP8266. Additionally, it provided for modification of the embedded web-server, to support more sophisticated control features via manual input.

4.2.2 Experiment 5: Wireless analogue control of dc load (brightness of an LED) using web graphical user interface

The luminosity of an LED was wirelessly modulated via a web Graphical User Interface (GUI) leveraging WiFi infrastructure. This modulation involved the manipulation of analog voltage levels to adjust the LED's brightness. To achieve this functionality, an analog web GUI was engineered using HTML and CSS, seamlessly integrated with an ESP8266 microcontroller unit. Varied luminance intensities of the analog LED were discerned by inputting analog values ranging from 0 to 1023 within the GUI. To enhance comprehension of the phenomenon, the experiment was conducted in low-light conditions, allowing for precise observation of the LED's response to user input commands via the web server. This experimental setup served as an educational instrument, fostering students' comprehension of foundational analog principles through remote, web-based interaction. Figure 7 shows schematic diagram of wireless analogue control of brightness of LED device.

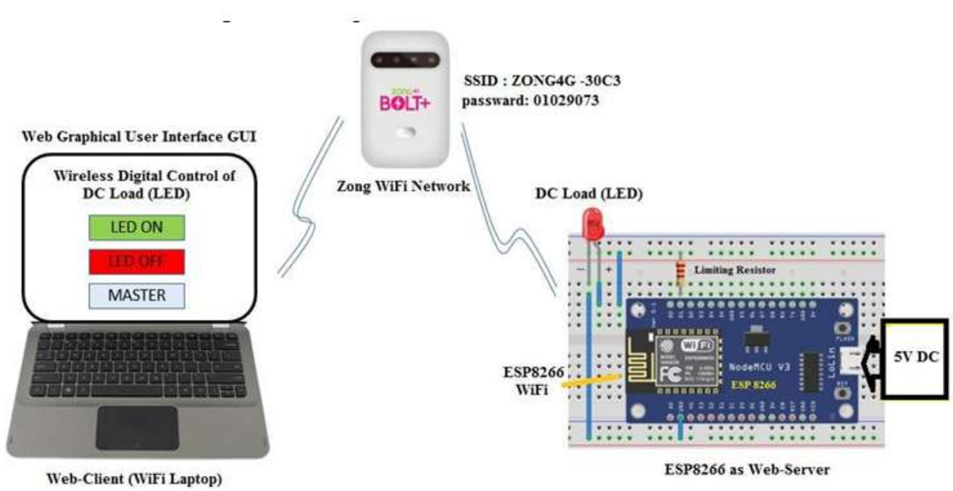

Figure 6. Schematic diagram of wireless digital control of dc load LED device using web GUI.

4.2.3 Experiment 6: Wireless digital control of single phase ac load (ac fan) using web graphical user interface

A single-phase 220V AC fan was interfaced with an ESP8266 web server via an electro- mechanical relay for Experiment 6. This innovative experiment aimed to facilitate the remote control of the AC load through WiFi internet connectivity. The AC fan was connected to the normally open contact of the electromechanical relay. A web-based Graphical User Interface (GUI) was developed, featuring buttons for initiating and terminating fan operation. The relay's operation was facilitated by its opto-coupler driver, which was intricately linked to the ESP8266 web server. Students were introduced to the utilization and intricacies of relays in conjunction with opto-couplers and embedded controllers. Moreover, the single-phase AC fan could be seamlessly replaced with any equivalent AC load, thereby enhancing the adaptability of the IIoT trainer setup. The functionality of the experiment was achieved with the thorough development of firmware for ESP8266 with the help of HTML, CSS, and chip coding in C++. Wireless digital control of single phase ac motor using web graphical user interface is shown in figure 8.

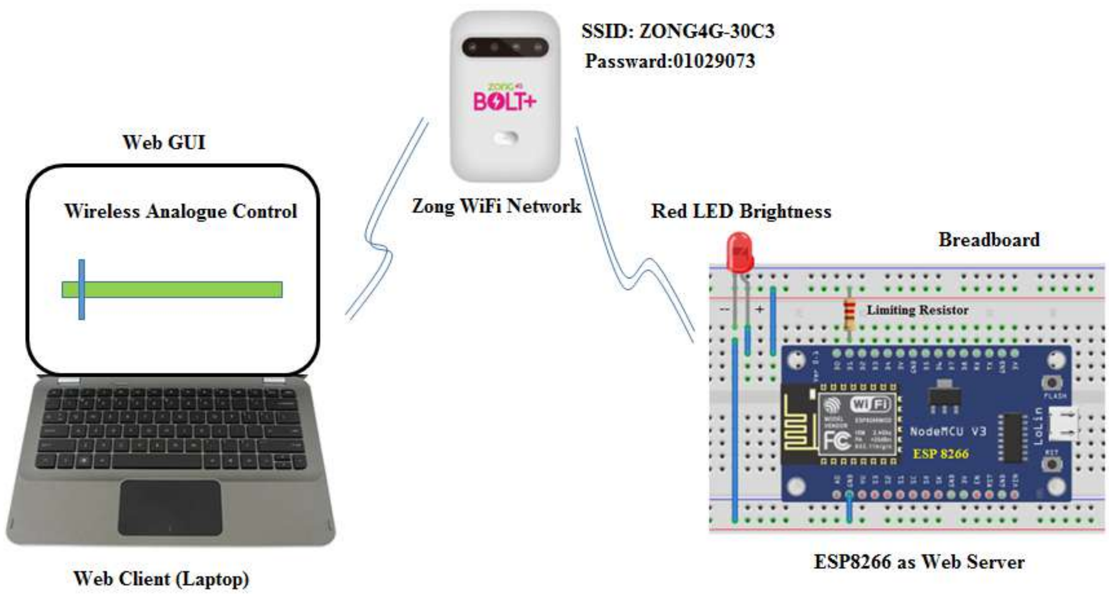

Figure 7. Schematic diagram of wireless analogue control of brightness of DC LED device.

4.2.4 Experiment 7: Wireless digital control of three phase ac load (three phase ac motor) via VFD and relay using web graphical user interface

The detailed knowledge of relays was obtained in the initial stages of the experiment. An electromagnetic relay was connected with an input control terminal of a variable frequency drive (VFD) controller. Specifically, the relay was connected to the forward control input terminal to turn on the VFD controller and further turn on the clockwise rotation of the three-phase motor. This motor with a rated power of 0.5 horsepower was connected to the output of VFD motor controller. Prior to experimentation, the VFD controller went through configuration modifications, such as a configuration of the acceleration, deceleration, torque, speed, and rotation direction, which were recorded in a table. To enable motor control, on/off buttons were included with the web graphical user interface (GUI). Figure 9 shows schematic of the proposed experiment 7.

The firmware algorithm was made using the tools of HTML, CSS, and C++ coding in an ESP8266 web server environment. Through this experiment, students learned the practical knowledge of how to configure the VFD parameters, interface the VFDs with relays at input control terminals and connect to three-phase motors at output control terminals.

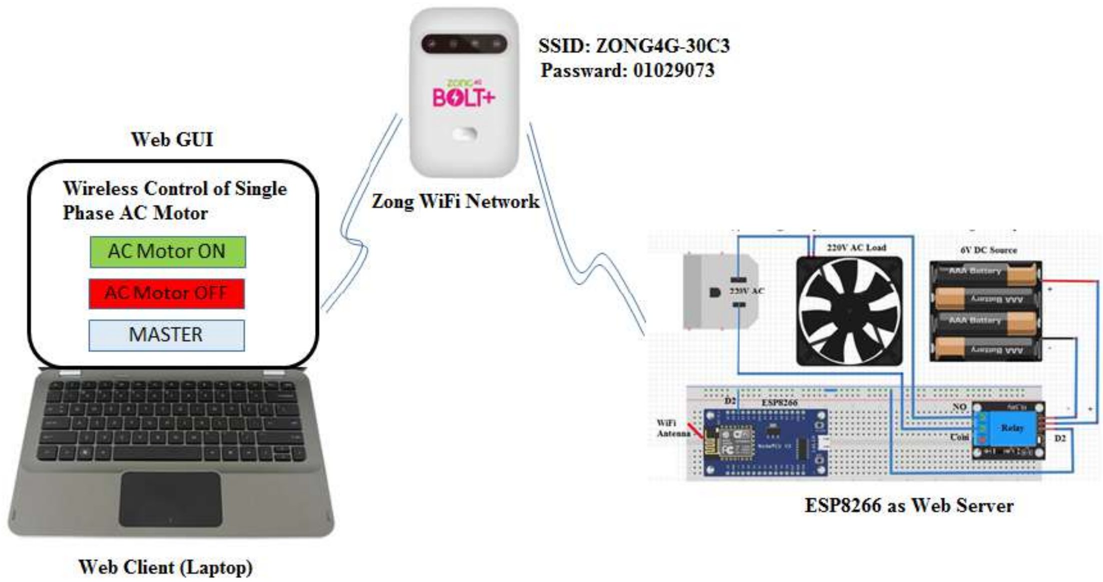

Figure 8. Schematic diagram of wireless control of single phase ac motor using web GUI.

The diagram in Figure 10 shows a simplified block diagram of an IIoT trainer that was designed for the student to be able to obtain essential IIoT skill sets. At its core is a 32-bit embedded controller, ESP8266, which has built-in WiFi to provide the wireless connectivity to a GUI over the web, without any cumbersome wires. The trainer kit has a red LED in it, which is used to illustrate the digital/analog concepts and the DC load functionalities.

Additionally, a relay-driven fan is one example of a single-phase 220V AC load, whereas a relay-operated VFD controller, attached to an AC motor, is one example of a three-phase AC load. This prototype comes at an affordable cost, which is estimated to fall between 65 to 70 US dollars. Its accessibility makes sure that students can acquire basic knowledge of IIoT, which will enable them to improve their industrial engineering skills effectively.

5 Discussion

5.1 System Performance and Load Control

The ESP8266-based IIoT trainer kit had demonstrated a proper performance in achieving hands-on IIoT learning, specifically in controlling industrial loads such as DC LEDs, DC motors, and simulated three-phase AC motors. The use of ESP8266 microcontroller ensured robust wireless connectivity at a low cost which enabled students to interact with devices using a web-based interface. Experimental results revealed a consistent performance of the system with an average latency of 1-2 milliseconds under different load conditions [65]. While slight variations were found mainly because of the difference between the circuit complexity of a DC and AC load. All responses fell within acceptable real-time thresholds, thus supporting the system's ability to provide educational functionality.

Educational Usability and Student Engagement Feedback from the practical sessions suggested that use of the trainer kit was an intuitive and easy to use experience. Students were able to set up and control the system with minimal supervision and the addition of a web-based graphics user interface (GUI) through the ESP8266 server made it much more accessible [68]. Above usability, the trainer provided the educational depth by exposing students to real world IIoT scenarios, such as wireless load control and basic network troubleshooting. These

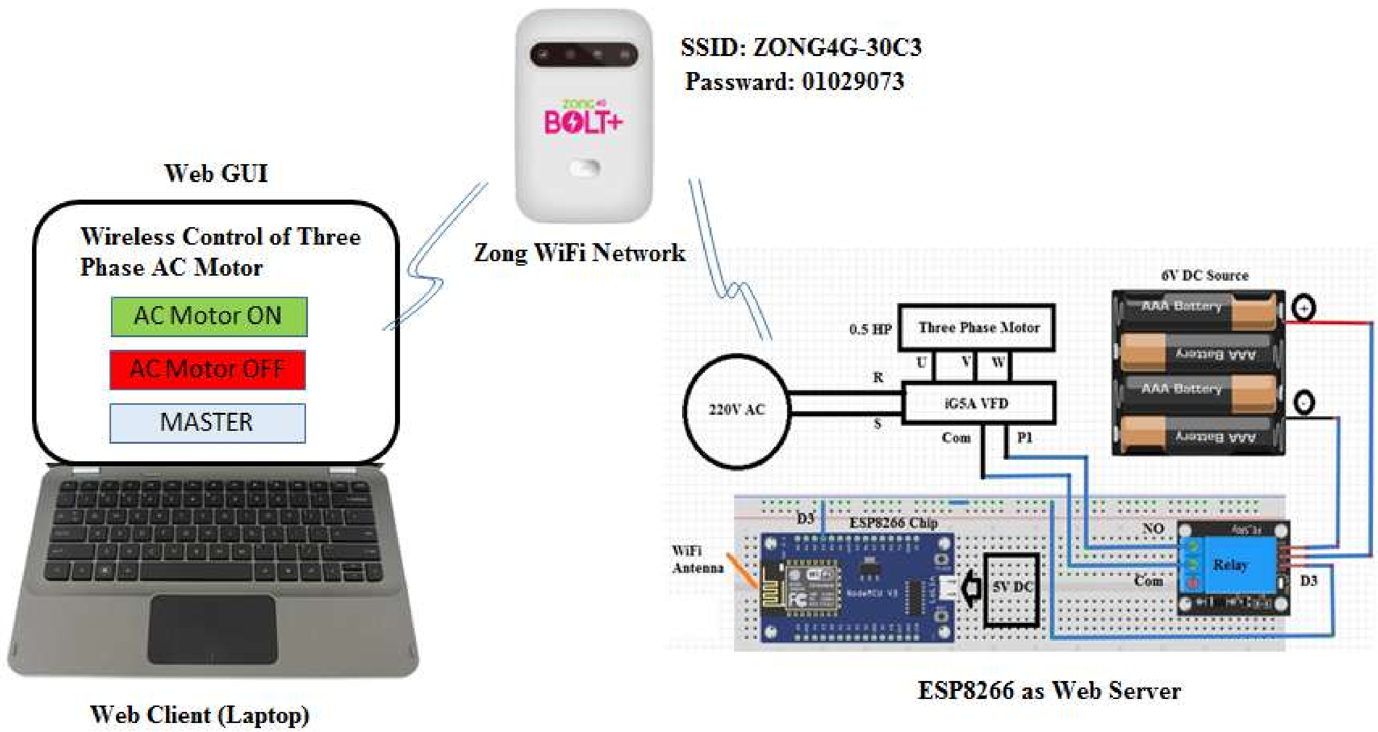

Figure 9. Schematic diagram of wireless control of VFD assisted three phase motor using web GUI.

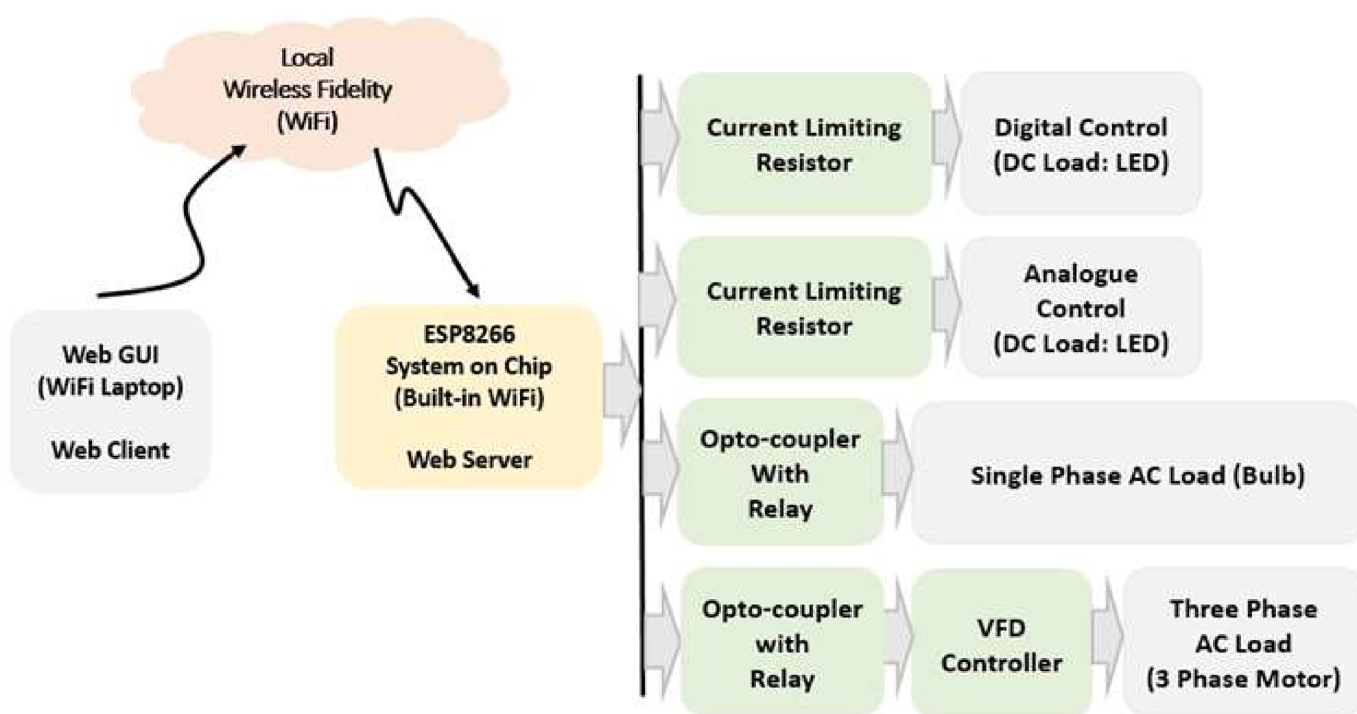

Figure 10. Simplified block diagram of IIoT training kit.

experiences helped learners acquire basic skills important for modern industrial automation, supporting the value of the kit as a pedagogical tool.

5.2 Modularity, Scalability, and Future Potential

The modular hardware architecture of the trainer kit supports scalability for seamless integration of additional components or replacement of existing components. This flexibility allows for experimentation and encourages students to investigate various configurations of IIoT. The flexibility of the system also makes it a basis for more advanced functions in future versions, such as integration of Bluetooth connectivity, sensor fusion, and edge analytics [70]. These enhancements would assist to simulate a whole IIoT environment, bridging the gap between introductory learning and real-world industrial applications.

Security Limitations and Improvement Needs Even though the kit has educational value, it also does not have the most important cybersecurity measures, which is required to implement IIoT in practice. At present the encryption and user authentication and access control functionality is lacking and this could prove to be the risk in the real world implementation. These features were set aside since the study had an instructional feasibility as its priority. However, introduction of elementary security measures in future design would provide more realism to the system and introduce the students to critical IIoT security measures. This trend is in accordance with the global trends, which are aimed at safe and robust IoT systems.

Power Usage and Environmental Sensitivity Power consumption analysis revealed that the energy consumption of them is more than DC components and should be considered when using it in long duration or in cases of using them off-grid. Moreover, the ESP8266 reliance on stable WiFi networks also created sensitiveness in the performance of the device in the cases of interference or low connectivity. All these limitations can be handled in a classroom setting, although they indicate that a better connectivity solution is required in case the kit is to be repurposed into industrial simulation or the field.

5.3 Comparative Advantage over Commercial Kits

In comparison to the commercially available IIoT training kits, the proposed solution presents an attractive price-quality-functionality balance of price, scalability, and practical usability. While high-end commercial kits can offer sophisticated capabilities, the expense and complexity can be a barrier to use in the academic setting - particularly in resource-poor areas such as Khyber Pakhtunkhwa, Pakistan. This ESP8266-based kit fills in a critical void by providing the essential IIoT concepts in an affordable and customizable platform, making it an ideal platform for foundational training. The ESP8266-based IIoT trainer kit has proven to be a good and accessible educational tool for teaching students about the main concepts of IIoT in a university environment. While it has been able to meet basic training needs, its current limitations such as lack of security features and limited range of available sensors provide a potential area for future enhancement. Integrating cybersecurity protocols and adding more sensors for temperature, pressure and other industrial metrics would provide a better representation of the real world of IIoT.

5.4 Conclusion of Discussion

To meet the rising demand for IIoT education in Khyber Pakhtunkhwa (KP) of Pakistan, the KP Science program, launched by the Directorate of Science and Technology, is aimed to equip students with practical skills required in the local industry. Traditional IIoT trainers tend to be costly and only available in private institutions, an accessibility gap. In light of this, this research presents a low-cost user-friendly IIoT trainer designed for beginners. The trainer is assisting them to know the basic concepts with the help of simple experiments like ESP8266-based Web server and wireless connectivity.

These hands-on activities prepare learners for employment by developing basic technical skills that will be relevant in KP's changing job market. Seven successful experiments were made to control wireless devices through the web GUI accessed via the ESP8266 server's IP address and the interface Google Chrome was used. The kit can be used with smart building applications such as lighting and HVAC control without any complicated wiring, which makes them ideal for remote or hazardous settings. Real time monitoring and control capabilities ensures the efficiency of its energy use and flexibility in its operations. Students and engineers can obtain experience by working with real hardware, and this experience assists them in bridging the gap between theory and practice. Its flexibility is favourable to the use in industrial automation and long-distance monitoring. Future enhancements involve the addition of analog sensors and creating SCADA system to enhance additional IIoT capabilities of the industrial environment of KP.

6 Conclusion

6.1 Expansion of Multi-Protocol Wireless Integration

The IIoT trainer kit should be developed in the future to include other types of wireless communication like LoRa, ZigBee and 5G in addition to WiFi. Particular strengths of these protocols in the industrial setting particularly in the domain of range, energy-efficiency and mesh network. As an example, the LoRa can be ideal in low-power and long-range communication between factory floors with large areas or even remote industrial areas. The self-healing mesh network of ZigBee can be used in the effort to raise the reliability of communication in the place of the high degree of interference. The combination of various protocols will provide more realistic conditions to IIoT and will allow students to understand the problem of interoperability.

Also, a performance analysis can be constructed into the curriculum comparing latency, bandwidth, and fault tolerance. This integration will equip learners with a wider scope of IIoT applications in different industries. It is also what opens the potential of smart city or agriculture application scalability in the future. To make the trainer more adjustable and rich in pedagogy, it would be necessary to change the trainer kit related to the modular wireless expansion.

6.2 Enhancing Data Analytics and Cloud Connectivity

To simulate the actual world of IIoT systems, better cloud integration and data analytics features ought to be provided to the trainer kit. Nowadays, sensor and device readings are frequently visualised on primitive web interfaces. The subsequent version may be connected to the cloud services such as AWS IoT, Google cloud IoT or Microsoft azure. Saving sensor data in cloud would allow students to understand how to apply analytics methodologies like trend analysis, anomaly detection, and predictive maintenance modeling. The tools are critical to the inefficiency of industrial processes and decision-making. ThingSpeak, Grafana, or Node-RED can be used to create real-time Dashboards. Such an extent of integration allows students to be taught not only at the device level about programming, but also at a level of higher level system engineering. The addition of cloud-based analytics will help in bridging the gap between hardware experimentation and industrial intelligence based on data.

6.3 Incorporation of Edge Computing Capabilities

Another promising direction for future work is the combination of edge computing functionalities. With the volume of data that will be produced by IIoT systems, processing all information in the cloud can cause latency problems and higher bandwidth costs. Edge computing helps to overcome this by enabling the processing of data at the device or gateway level. The trainer kit can be extended by using more powerful microcontrollers or single-board computers such as the ESP32 and the Raspberry Pi. These can do preliminary data analysis, decision making, and event detection and then pass on important data to the cloud. This teaches students about the hierarchical processing and optimization of systems. It also coincides with industrial practices where time-critical decisions have to be carried out in milliseconds. Furthermore, edge processing increases the security of the data by reducing the amount of data transmission and reduces the dependence on the cloud. The addition of edge computing to the educational kit will add a great deal of technology and relevancy to the kit.

6.4 Integration of Industrial Protocols and Standards

Currently, the kit runs using simple communication using the web interface using the basic communication protocol of the Internet. However, there are standardized protocols used in real industrial environments: MQTT, Modbus, OPC UA and CAN bus, to name a few. Adding support for these protocols will ensure the trainer kit is more industry compliant and educational. For example, MQTT is ideal for IIoT because it is a lightweight and publish/subscribe model. Modbus and OPC UA are widely used in factory automation and SCADA systems. Including these in future versions will provide students with hands-on experience in handling real-time industrial communications. This could be achieved by integrating open-source libraries and protocol converters. It was then possible to simulate factory conditions, inter-device communication, and fault-handling mechanisms by students. In addition, their study of these standards equips them with an automation and control engineering career. This addition will fill the gap between academic education and industry needs and enhance curriculum alignment.

6.5 Development of a Scalable Modular Design

A design of a modular trainer kit can greatly increase its usefulness, personalization and learning techniques. Modularization allows instructors and students to swap or upgrade particular components, including microcontrollers, sensors or type of load, based on particular learning goals. Such a design would encourage experimentation and innovation as well as cater to other levels of courses, such as beginner and advanced. Types of modules could be analog and digital sensor packs, motor drivers, security modules and protocol adapters. These may be plug and play or bus architecture connected. Modular approach also allows team learning where students work in groups to combine and experiment with various modules. Moreover, a modular system is easy to maintain and update the system in the future. The teachers are able to create standardized experiments where gaps are left to allow the students to make extensions and innovations. The kit may eventually turn into such a platform as capstone projects and academic competitions.

6.6 Emphasis on Cybersecurity and System Hardening

Although the existing trainer kit is about connectivity and control, new versions will have to have the capability of ensuring strong cybersecurity to match the security issues in a realistic industrial environment. This involves use of encryption(SSL/TLS), secure authentication, firmware integrity checks and access control measures. There are educational modules that may be used to educate students on how to detect and prevent such risks as man-in-the-middle attacks, DoS attacks or unauthorized access to the device.Wireshark could be used to monitor network traffic and perform ethical penetration attacks. Moreover, introducing cybersecurity will enable students to know the essential tradeoff between openness and security in IIoTs. By adding watchdog timers and secure firmware updates, the problems in the system will be shown to be resilient to true industrial systems. The concept of Security-by-design needs to be included in the learning process to equip students with the skills needed to work in the field of industrial IT and OT security. In this way, the trainer kit will no longer be an ordinary learning tool but a complete secure IIoT learning platform.

Author Contribution

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Compliance with Ethical Standards

Declare any potentially competing interests, financial or otherwise see the example It is declared that all authors don't have any conflict of interest. It is also declared that this article does not contain any studies with human participants or animals performed by any of the authors. Furthermore, informed consent was obtained from all individual participants included in the study.

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