

## **DESIGN AND EXPERIMENTAL EVALUATION OF A PORTABLE AIOT-ENABLED AUTOMATION PLATFORM FOR ENGINEERING LABORATORIES**

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### **Abstract**

This paper presents REPAL, a portable AIoT-enabled automation platform. In this study, AIoT-enabled means that IoT-connected automation is combined with a separate offline anomaly-detection learning activity. The AI model is not part of the real-time control loop. The platform uses a Siemens PLC, industrial input and output devices, an edge gateway, MQTT, Node-RED, cloud dashboards and an offline Isolation Forest activity for introductory anomaly detection. It accommodates various practical configurations, such as PID temperature control and variable frequency drive motor control. We tested the platform in three ways. These tests included local-network communication, PID temperature response, and offline anomaly detection using Isolation Forest. During the network test, all packets were received, and the average round-trip delay was below 1 ms. In the PID test, REPAL achieved the 50°C setpoint region in approximately 50 seconds, with a 4% overshoot. The platform was further used in two five-day workshops involving 26 participants, with 25 complete pre- and post-workshop response pairs analysed. All five self-reported competency ratings increased after the workshop, and the differences were statistically significant at  $p < 0.001$ . The results show that REPAL can support industrial automation practice, IoT communication, cloud monitoring and introductory anomaly-detection activities in one portable platform.

Keywords: AIoT; Edge gateway; Industrial automation; Programmable logic controller; Technical training.

## 1. Introduction

Industrial automation increasingly combines PLCs, sensors, IoT communication, edge/cloud monitoring and data analysis. AIIoT extends this by combining connected devices with machine-learning functions [1]. These developments, together with Industry 4.0 and Industry 5.0 trends, create new skill requirements for engineers [2-3]. In this study, AIIoT-enabled refers to IoT-connected automation combined with a separate offline anomaly-detection activity; AI does not control the real-time process.

Traditional laboratories remain important for PLC programming, motor control and sensor-actuator work, but many provide limited exposure to connected IoT/cloud workflows and data-analysis activities. REPAL was developed as a portable platform that combines a PLC, industrial I/O, interchangeable edge gateways, MQTT, Node-RED, cloud monitoring, PID/VFD activities and an offline anomaly-detection exercise. It was evaluated through technical tests and two five-day workshops.

### 1.1. Related work and research gap

Earlier platforms have combined industrial control with remote or IoT-based learning. MERP integrated industrial control and IoT activities [5]. Domínguez et al. [6] used a PLC, Modbus TCP, Node-RED and MQTT with a remote pilot plant, while Higginson and Brooks [7] combined a Siemens PLC/SCADA system with Arduino, Raspberry Pi, MQTT and ThingSpeak.

More recent systems include an industrial-scale remote laboratory with six experimental setups [8], a cloud/IoT FPGA motor-control laboratory evaluated with 50 students [9], an AIIoT smart-farming platform evaluated with 40 students [10], and modular PLC training kits reported to reduce laboratory cost [11]. These studies address remote control, IoT/cloud learning, AIIoT activities and modular PLC training.

The reviewed systems address different parts of automation education, including remote industrial control, IoT/cloud learning, AIIoT activities and modular PLC training. However, none of the selected studies combines these functions around portable industrial control hardware. REPAL addresses this gap by integrating a Siemens PLC and I/O, interchangeable edge gateways, MQTT/Node-RED communication, cloud monitoring, PID/VFD activities and introductory offline anomaly detection in one reconfigurable platform. Its contribution is therefore system integration rather than a new PLC, protocol or AI algorithm.

### 1.2. Aims and objectives

This study presents the development and experimental evaluation of a portable AIIoT-enabled automation platform. The main objectives are:

- To develop a portable and reconfigurable platform that integrates industrial PLC control, IoT communication, cloud monitoring and an introductory offline anomaly-detection activity.
- To verify the main technical functions of REPAL through local-network connectivity testing, a 50°C PID temperature-control activity and an offline anomaly-detection demonstration using collected machine data.

- To evaluate participants' self-reported competency and perceptions using 25 matched pre- and post-workshop TEQ responses together with post-workshop SAQ and QRI ratings.

### 1.3. Research questions

Based on the objectives of the study, the following research questions were used:

- **RQ1:** How can a portable and reconfigurable platform integrate industrial PLC control, edge and IoT communication, cloud monitoring and introductory anomaly detection for engineering laboratory use?
- **RQ2:** How does REPAL perform in the selected technical evaluations of local-network communication, PID temperature control and offline anomaly detection?
- **RQ3:** How do participants' self-reported competency and perceptions change after using REPAL during the workshop activities?

### 1.4. Contributions

The main contributions of this study are:

- A portable and reconfigurable platform that integrates industrial PLC/I/O, interchangeable edge gateways, MQTT, cloud monitoring and PID/VFD practical activities.
- Integration of an introductory offline anomaly-detection activity while keeping real-time control local, together with technical evaluation of network connectivity, PID response and the anomaly-analysis workflow.
- Participant evaluation using pre/post self-reported competency measures, usability ratings and item-level feedback.

## 2. Platform Design and Experimental Procedure

### 2.1. System architecture

REPAL combines industrial control hardware, an edge gateway, IoT communication, cloud monitoring and an offline anomaly-detection activity in one portable system. The main design aim was to provide reliable PLC control while also allowing users to practise IoT communication and basic data-analysis activities. The PLC and IoT functions operate independently of the offline anomaly-detection exercise.

The platform consists of two main parts:

- a main panel containing the PLC, industrial input/output devices, power supplies and protection components.
- an application panel used for motor-control experiments, sensor connection and user prototyping.

The PLC handles digital and analogue I/O, sensors and actuators. The edge gateway manages Node-RED, MQTT, data logging and cloud connections through Ethernet or Wi-Fi. This separation between local control and higher-level data processing reflects common industrial automation and IoT architectures [2, 7].

REPAL supports more than one hardware configuration. The gateway can be either a Siemens IoT2040 or a CM4-based Pi-IRIV gateway. The platform can also be configured for PID-based temperature control or VFD-based motor control. Although the hardware changes between the configurations, the same general workflow is maintained. This workflow includes data collection, PLC control, MQTT communication, dashboard monitoring and data analysis.

The overall architecture of REPAL is illustrated in Fig. 1, showing the flow from field devices and PLC control to edge processing, MQTT communication, cloud services and offline AI-based analytics.

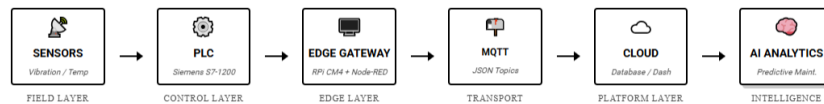


Fig. 1. Layered architecture of the REPAL platform.

## 2.2. Hardware implementation

A Siemens S7-1200 PLC was used as the main controller. It was programmed using TIA Portal and was responsible for control logic, digital and analogue signal handling and communication with field devices.

The main hardware included a Siemens S7-1200 PLC, Siemens IoT2040 or CM4-based Pi-IRIV gateway, SM1231 analogue input module, Delta DTA4848 PID controller, temperature/light sensors, relays, contactors, servo and VFD loads, regulated 24 VDC and 5 VDC supplies, protection devices and external I/O terminals.

High-voltage wiring and industrial components were enclosed inside the main panel. The application area remained accessible so that users could connect sensors and actuators without opening the protected section.

## 2.3. Software and communication

Node-RED connected the PLC, sensors, MQTT broker, cloud services and dashboards [7]. Its visual programming interface also supported participants with different programming experience.

MQTT provided publish-and-subscribe communication [813]. Participants sent PLC and sensor data and used web or mobile interfaces for supervisory commands. Mosquitto, Adafruit IO and ThingSpeak supported different workshop tasks.

Adafruit IO was used for simple MQTT dashboards and remote control, while ThingSpeak was used to store, display and analyse data.

The anomaly-detection activity used Isolation Forest in a Python Jupyter notebook [14] with spindle speed, machine load and temperature as inputs. The model used 100 estimators and contamination = 0.02. It ran offline on unlabelled data to introduce unsupervised anomaly detection. It was not connected to the PLC control loop, did not make real-time decisions, and was not used to confirm faults or measure diagnostic accuracy.

## 2.4. Physical layout and modular configurations

The physical design was prepared for safe use and easy movement between different laboratory locations. Industrial wiring and higher-voltage parts were placed inside the enclosed main panel. The open application panel provided access to low-voltage terminals, breadboards, sensors and actuators.

Two representative configurations were used:

- a PID temperature-control configuration using the Delta controller, temperature sensor and heating element.
- a motor-control configuration using PLC outputs, contactors and an optional VFD.

The modular design allowed the gateway or control module to be changed without rebuilding the complete platform.

Two representative hardware implementations of REPAL are shown in Fig. 2. These configurations demonstrate the platform's modularity for both motor-control and temperature-control applications.



**Fig. 2. Representative REPAL configurations: (a) VFD-based motor-control configuration and (b) PID temperature-control configuration.**

## 2.5. Workshop activities

Two five-day workshops moved from basic PLC control to IoT communication, cloud dashboards and offline anomaly detection. The sequence of activities conducted during the workshops is summarised in Table 1.

**Table 1. Main activities conducted during the REPAL workshop.**

| Main Focus                    | Practical Activity                                                    |
|-------------------------------|-----------------------------------------------------------------------|
| 1 PLC and automation basics   | PLC connection, TIA Portal project and digital I/O testing            |
| 2 Sensors and process control | Analogue signal reading and PID temperature control                   |
| 3 Node-RED and MQTT           | PLC data publishing, subscription and dashboard creation              |
| 4 Cloud and anomaly analysis  | Adafruit IO, ThingSpeak and anomaly-detection demonstration           |
| 5 System integration          | Integrated automation and IoT mini-project and participant evaluation |

## 2.6. Technical validation procedure

Three technical tests were used to examine the basic operation of the REPAL platform. The technical checks were selected to verify the main functions needed during the laboratory activities: local connectivity for IoT data exchange, closed-loop temperature control and the offline anomaly-analysis workflow.

### 2.6.1. Local-network and IoT communication checks

The local network connection between the test computer and the main REPAL network devices was checked using ICMP echo requests. A total of 100 packets were sent to each selected device. Packet loss and average round-trip delay were recorded.

The MQTT and cloud functions were checked during the workshop by publishing process values and system states to Node-RED, mobile interfaces and cloud services. These checks confirmed that the communication path was working for the laboratory activities. However, end-to-end MQTT latency, jitter, message loss, update rate and cloud response time were not measured separately. The ICMP results therefore represent only local-network connectivity and should not be treated as application-level communication performance.

### 2.6.2. PID temperature-control test

The PID temperature-control configuration was tested using a temperature setpoint of 50°C. The recorded measures were starting temperature, rise time, maximum temperature, percentage overshoot and steady-state temperature.

The PID temperature-control setup used a Delta DTA-4848 controller, a PT100 temperature sensor, a water container and an electric heater. The temperature setpoint was 50°C, and the REPAL test started at 29°C. Temperature was recorded until the response reached a stable operating region. The heater input was also adjusted manually during the practical test.

The REPAL response was compared with a conventional fixed laboratory PID trainer using the same 50°C setpoint. This comparison was intended only as a practical functional check. The two systems did not start under the same conditions, and the heater/load conditions were not fully matched. The controller gains, internal PID sampling interval and room ambient conditions were not recorded in the experimental log. Repeated matched trials and integral error measures were also not part of the original test. For this reason, the comparison is not treated as a controlled controller-performance benchmark.

The percentage overshoot was calculated using Eq. (1):

$$\text{Overshoot (\%)} = \frac{T_{\max} - T_{\text{set}}}{T_{\text{set}}} \times 100 \quad (1)$$

where  $T_{\max}$  is the maximum recorded temperature and  $T_{\text{set}}$  is the required setpoint.

### 2.6.3. Anomaly-detection demonstration

Operational data were collected through Node-RED and stored as time-based datasets. Each analysed session contained approximately 3,000–5,000 samples. The model used spindle speed, spindle load and temperature as input features. Spindle speed was recorded in rpm, spindle load in %, and temperature in °C. In

the retained dataset, spindle speed ranged approximately from 1480 to 1520 rpm, spindle load from 35 to 45%, and temperature from 63 to 67°C.

Before model fitting, non-numerical fields were removed, and the three input features were standardised using `StandardScaler`. The timestamp was retained only for plotting and was not used as a model input. Isolation Forest was implemented in Python using Jupyter Notebook with 100 estimators, `contamination = 0.02` and `random_state = 42`. The model was fitted to the scaled operational dataset collected under mainly normal operating conditions. The same dataset was then used to demonstrate anomaly flagging and visualisation. No separate training and test datasets were used because the activity was intended as an educational demonstration rather than a predictive-performance study.

The `contamination` setting was used to define the expected proportion of unusual samples. The model therefore flagged only a small part of the fitted dataset. Since no labelled fault data were available, the flagged samples represent unusual operating points and not confirmed machine faults.

## 2.7. Participant evaluation

### 2.7.1. Participants and study setting

A total of 26 participants took part in two university-arranged five-day workshops. The group included undergraduate and postgraduate students, lecturers and technical trainers from electrical, electronic, mechatronic, computer and related engineering areas. Participants were recruited from the workshop attendees, while participation in the research evaluation was voluntary.

Both workshops followed the same five-day sequence, practical activities and evaluation process and were delivered under the same general laboratory conditions. The same lead instructor conducted the main training activities. All participants completed the same core tasks. A total of 25 complete pre- and post-workshop response pairs were available for paired analysis.

### 2.7.2. Evaluation instruments

Three instruments assessed self-reported competency and participant experience. TEQ, SAQ and QRI were adapted from the earlier MERP study [65] and matched the REPAL activities. TEQ covered automation, programming and IoT skills; SAQ covered platform quality and interactivity, technical understanding, learning support and convenience; and QRI covered practical tasks, IoT application development and platform usefulness.

The structure and content of the evaluation instruments used in this study are summarised in Table 2.

All questionnaire items used a five-point scale: 1 = Very Poor, 2 = Poor, 3 = Satisfactory, 4 = Good and 5 = Very Good.

The TEQ was completed before and after the workshop. The SAQ and QRI were completed after the workshop.

Cronbach's alpha was used to examine internal consistency. TEQ alpha values were 0.893 before and 0.898 after the workshop, while SAQ was 0.760. QRI was

lower at 0.522; because its three items covered different areas, they were analysed separately rather than as one combined scale.

**Table 2. Summary of participant evaluation instruments.**

| <b>Instrument</b> | <b>Questionnaire items</b>                                                                                                                                                                          |
|-------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| TEQ (5 items)     | TEQ1: Sensor and actuator skills; TEQ2: Programming skills; TEQ3: IoT communication protocol skills; TEQ4: IoT web application development skills; TEQ5: IoT mobile application development skills. |
| SAQ (4 items)     | SAQ1: Level of interactivity and overall technical quality; SAQ2: Technical understanding of REPAL; SAQ3: Support for learning IoT technology; SAQ4: Convenience of learning IoT with REPAL.        |
| QRI (3 items)     | QRI1: Ability to perform analogue and digital I/O tasks; QRI2: Ability to design and program IoT applications without software or hardware issues; QRI3: Usefulness of the current REPAL features.  |

### 2.7.3. Statistical analysis

Paired-sample t-tests compared the pre- and post-workshop TEQ scores for the 25 matched responses ( $d_f = 24$ ). Means, standard deviations, mean differences, 95% confidence intervals, t-values, p-values and Cohen's  $d_z$  were reported [13].

Because the TEQ items use an ordinal five-point scale, Wilcoxon signed-rank tests were also used as a non-parametric sensitivity check. The same conclusion was obtained for all five items ( $p < 0.001$ ). Five separate TEQ comparisons were performed; therefore, a Bonferroni-adjusted significance level of 0.01 was also considered. All five results remained significant under this adjustment.

SAQ and QRI results were analysed using descriptive statistics. Frequencies and percentages were used to describe participant opinions about platform usability, technical understanding and overall usefulness.

Reliability analysis used all 26 responses, while paired analysis used the 25 matched pre- and post-workshop responses.

### 2.7.4. Ethics statement

The study was conducted under the university's master's research process. At the time of the study, the university did not have a formal research ethics committee; therefore, no institutional ethics approval or reference number was available. The academic approval of the Master's project is not presented as ethics approval. Participants were informed about the purpose of the study before completing the questionnaires. Participation was voluntary, informed consent was obtained, and questionnaire responses were collected anonymously.

## 3. Results and Discussion

This section presents the technical and participant results. RQ2 is addressed through functional tests of network communication, PID temperature control and offline anomaly detection. RQ3 is addressed through participant ratings and

comments. RQ1 is addressed by the platform design in Section 2 and its comparison with earlier work in Section 3.6.

### 3.1. Technical performance results

#### 3.1.1. Local-network and IoT communication behaviour

The supervisory computer was connected to the two main REPAL devices. A total of 100 ICMP packets were sent to each device. The results are shown in Table 3.

**Table 3. Local-network communication test results.**

|                            | Sent | Received | Loss | Average delay |
|----------------------------|------|----------|------|---------------|
| <b>Siemens PLC</b>         | 100  | 100      | 0%   | <1 ms         |
| <b>Pi-IRIV CM4 gateway</b> | 100  | 100      | 0%   | <1 ms         |

All 100 packets sent to each device were received, with an average round-trip delay below 1 ms, confirming stable local connectivity during the test. MQTT was also used successfully during the workshops to transfer process values and system states to Node-RED, mobile interfaces and cloud services.

The PLC and PID controller handled real-time control locally, while MQTT/cloud services supported monitoring, logging and supervisory interaction. End-to-end MQTT latency, message loss, update rate and cloud response time were not measured; therefore, the results represent functional IoT communication rather than a complete communication-performance benchmark.

#### 3.1.2. PID temperature-control results

The REPAL PID configuration was tested using a temperature setpoint of 50°C. The initial temperature was 29°C. The temperature reached the setpoint region after approximately 50 seconds and remained mainly between 50°C and 51°C. The highest recorded temperature was 52°C.

The result was compared with a conventional fixed PID laboratory trainer. Table 4 presents the main results.

**Table 4. Practical temperature-response comparison between the conventional trainer and REPAL.**

|                              | Conventional laboratory setup | REPAL   |
|------------------------------|-------------------------------|---------|
| <b>Setpoint</b>              | 50°C                          | 50°C    |
| <b>Initial temperature</b>   | Ambient temperature           | 29°C    |
| <b>Rise time</b>             | 60 s                          | 50 s    |
| <b>Maximum temperature</b>   | 53°C                          | 52°C    |
| <b>Overshoot</b>             | 6%                            | 4%      |
| <b>Final operating range</b> | Approximately 50°C            | 50-51°C |

Based on Eq. (1), the conventional setup had an overshoot of 6% because its maximum temperature was 53°C at a setpoint of 50°C. REPAL reached a maximum temperature of 52°C, which gave an overshoot of 4%.

REPAL reached the 50°C setpoint region after about 50 s and remained mainly between 50°C and 51°C. The conventional trainer reached the setpoint in about 60 s. REPAL recorded a maximum temperature of 52°C, while the conventional setup reached 53°C. These values are reported as descriptive observations only. Since the starting conditions and heater input were not matched, the results cannot be used to conclude that one controller performed better than the other.

The temperature-response profiles of REPAL and the conventional laboratory setup are presented in Fig. 3.

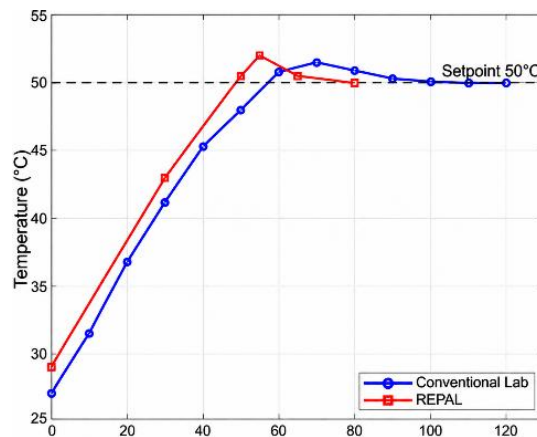


**Fig. 3. Temperature responses of REPAL and the conventional PID laboratory setup at a setpoint of 50°C.**

The test therefore confirms that the REPAL temperature-control configuration could operate around the selected setpoint, but it does not provide a controlled comparison of controller quality.

### 3.1.3. Offline anomaly-detection demonstration

Isolation Forest was applied to spindle speed, machine load and temperature. About 3,000–5,000 samples were logged during the analysed session, and 2.2% were flagged as unusual, which is close to the 0.02 contamination setting. Most samples represented stable operation.

The same operational dataset was used for model fitting and visualisation, so the result does not represent out-of-sample detection performance. The PLC scan time was about 5–10 ms, while anomaly-analysis data were sampled every 500–1,000 ms. The model ran offline and was not part of the control loop. Because labelled fault data were unavailable, the flagged samples cannot be treated as confirmed faults or used to calculate accuracy, precision or recall. A validated fault-diagnosis study would require labelled operating conditions and controlled fault experiments.

The Isolation Forest results are visualised in Fig. 4, including the detected unusual samples in the time series and the relationship between spindle speed and temperature.

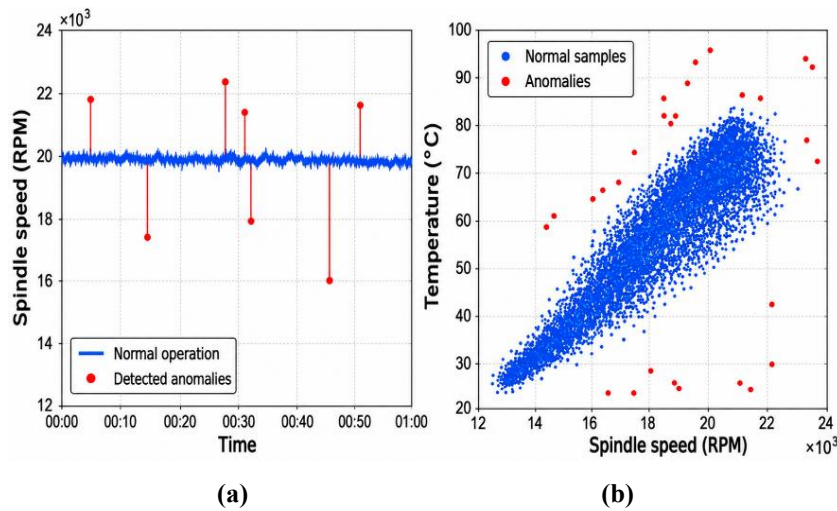


**Fig. 4. Isolation Forest results: (a) spindle-speed data with detected unusual samples and (b) relationship between spindle speed and temperature.**

### 3.2. Participant overview

A total of 26 participants joined two workshop sessions, with each session lasting five days. The group included undergraduate students, postgraduate students, lecturers and technical trainers from different engineering backgrounds.

The distribution of the 26 participants is shown in Table 5. Twenty-five participants provided complete matched pre- and post-workshop responses for the paired analysis.

**Table 5. Distribution of workshop participants.**

| Participant group                             | Frequency | Percentage  |
|-----------------------------------------------|-----------|-------------|
| Electrical and electronic engineering         | 14        | 53.8%       |
| Mechatronics and computer science engineering | 7         | 26.9%       |
| Lecturers, trainers and other participants    | 5         | 19.2%       |
| <b>Total</b>                                  | <b>26</b> | <b>100%</b> |

### 3.3. Teaching evaluation questionnaire results

The TEQ was completed before and after the workshop. It measured five competency areas related to automation, programming and IoT application development. The paired-sample t-test results are presented in Table 6.

All five post-workshop ratings were higher ( $p < 0.001$ ), with Cohen's  $d_z$  ranging from 0.98 to 2.45. The largest increase was for IoT web application development, followed by IoT communication and mobile application development. These are self-reported changes and should not be treated as direct measures of practical skill.

Sensor/actuator and programming scores increased less and also started higher, suggesting more prior experience in basic automation than in IoT applications.

**Table 6. Paired-sample t-test results for TEQ items.**

|                                           | Pre mean    | Post mean   | Mean diff | 95% CI      | t     | p      | $d_z$ |
|-------------------------------------------|-------------|-------------|-----------|-------------|-------|--------|-------|
| <b>Sensor and actuator skills</b>         | 2.56 ± 1.42 | 3.80 ± 0.65 | 1.24      | 0.731–1.749 | 5.02  | <0.001 | 1.00  |
| <b>Programming skills</b>                 | 2.64 ± 1.08 | 3.60 ± 0.65 | 0.96      | 0.556–1.364 | 4.91  | <0.001 | 0.98  |
| <b>IoT communication protocols</b>        | 2.08 ± 1.15 | 3.92 ± 0.70 | 1.84      | 1.353–2.327 | 7.80  | <0.001 | 1.56  |
| <b>IoT web application development</b>    | 1.80 ± 0.87 | 3.80 ± 0.71 | 2.00      | 1.663–2.337 | 12.25 | <0.001 | 2.45  |
| <b>IoT mobile application development</b> | 1.76 ± 0.97 | 3.52 ± 0.71 | 1.76      | 1.265–2.255 | 7.33  | <0.001 | 1.47  |

### 3.4. Self-assessment questionnaire results

The SAQ asked participants about the platform's quality, technical understanding, support for learning and convenience. The results are presented in Table 7.

**Table 7. Distribution of SAQ responses.**

|                                | Very Poor | Poor | Satisfactory | Good | Very Good |
|--------------------------------|-----------|------|--------------|------|-----------|
| <b>Platform quality</b>        | 0         | 0    | 6            | 11   | 9         |
| <b>Technical understanding</b> | 0         | 0    | 6            | 15   | 5         |
| <b>Learning support</b>        | 0         | 0    | 7            | 10   | 9         |
| <b>Convenience</b>             | 0         | 1    | 6            | 9    | 10        |

Good or Very Good was selected by 20 participants for platform quality and technical understanding, and by 19 for learning support and convenience. Only one Poor response and no Very Poor responses were recorded.

### 3.5. Questionnaire regarding improvement results

The QRI asked participants about their ability to complete practical tasks and their opinion of the current REPAL features.

Participant responses to the QRI instrument are summarised in Table 8.

**Table 8. Distribution of QRI responses.**

|                                                          | Very Poor | Poor | Satisfactory | Good | Very Good |
|----------------------------------------------------------|-----------|------|--------------|------|-----------|
| <b>Ability to perform analogue and digital I/O tasks</b> | 0         | 1    | 7            | 11   | 7         |
| <b>Ability to develop IoT applications</b>               | 0         | 0    | 7            | 11   | 8         |
| <b>Usefulness of current REPAL features</b>              | 0         | 0    | 2            | 12   | 12        |

Good or Very Good was selected by 18 participants for practical I/O tasks, 19 for IoT application development and 24 for the usefulness of REPAL features.

These results reflect participant opinion and do not directly measure long-term technical performance.

### 3.6. Participant comments and comparison with earlier work

An optional open-ended question was included in the post-workshop Google Form. Eleven of the 26 participants provided written comments. The comments were reviewed descriptively rather than through formal qualitative coding. Several comments were positive about the workshop or usefulness of the platform. Three participants specifically referred to learning or understanding new IoT/AIoT concepts, while three mentioned the value of seeing sensors, cloud services and AI connected in one workflow. One participant suggested extending the workshop duration, and one highlighted the convenience of the portable platform compared with a fixed laboratory setup. Informal verbal comments were also received during the workshops, but these were not included in the reported counts.

Table 9 compares REPAL with selected educational automation and IoT platforms [5-1211] in terms of hardware, connectivity, portability and evaluation.

**Table 9. Comparison of REPAL with selected educational automation and IoT laboratory platforms.**

| Study                     | Hardware                                     | IoT/ Cloud                        | AI/ ML                   | Portability                                                | Evaluation                                                |
|---------------------------|----------------------------------------------|-----------------------------------|--------------------------|------------------------------------------------------------|-----------------------------------------------------------|
| MERP [5]                  | Industrial PLC and application panels        | IoT/cloud functions               | No                       | Multiple application panels                                | Workshop participant evaluation                           |
| Domínguez et al. [6]      | PLC and real pilot plant                     | Modbus TCP, Node-RED, MQTT        | No                       | Remote access; fixed plant                                 | PID laboratory activity                                   |
| Higginson and Brooks [7]  | Siemens PLC, SCADA, Arduino and Raspberry Pi | MQTT and ThingSpeak               | No                       | Remote access; fixed process plant                         | Real process-control operation                            |
| Yapakçi et al. [8]        | Industrial automation equipment; six setups  | Remote/IoT architecture           | No                       | Remote access; fixed laboratory                            | Six experimental setups deployed                          |
| Guerrero-Osuna et al. [9] | FPGA and motor hardware                      | IoT and cloud                     | No                       | Remote laboratory                                          | 50 students and survey                                    |
| Chookaew et al. [10]      | Arduino and environmental sensors            | AIoT platform                     | Yes                      | Educational smart-farming setup                            | 40 students; pre/post evaluation                          |
| Al-Yaman et al. [12]      | PLC, HMI, sensors and actuators              | Mainly local PLC/HMI              | No                       | Modular kits; ten trainee pairs                            | Hardware validation; cost about 27% of conventional setup |
| REPAL                     | Siemens S7-1200 and industrial I/O           | MQTT, Node-RED and cloud services | Offline Isolation Forest | Portable; interchangeable gateways; PID/VFD configurations | Technical tests + 26 participants; 25 paired responses    |

Recent studies also report positive learner responses to cloud/IoT and AIIoT laboratory activities [9, 10]. REPAL showed a similar positive direction, although its competency results are self-reported and should not be interpreted as direct practical-skill evidence.

A fully quantitative comparison was not possible because the reviewed studies use different measures of cost, deployment, experiments and scalability. Table 9 therefore reports comparable values where available. REPAL mainly differs through the integration of portable industrial PLC control, interchangeable edge gateways, MQTT/Node-RED, cloud monitoring and introductory anomaly analysis in one reconfigurable platform.

3.7. Study limitations

The study used a small single-group sample (26 participants; 25 matched pairs) without a control or comparison group. Therefore, the observed changes in self-reported competency cannot be attributed exclusively to REPAL. TEQ measured self-reported competency rather than direct practical skill. TEQ and SAQ showed acceptable internal consistency, while QRI showed lower consistency ( $\alpha = 0.522$ ) and was therefore interpreted item by item. Technical limitations include unlabelled offline anomaly data, ICMP-only network testing and a single PID comparison under unmatched conditions. PID gains, controller sampling time, ambient conditions, repeated trials and integral error measures were not recorded. Larger multi-institution studies with practical assessment are needed.

4. Conclusion

REPAL combines a Siemens PLC, industrial I/O, an edge gateway, MQTT, Node-RED, cloud monitoring and offline anomaly detection for PID and VFD activities. Technical tests showed no packet loss, average round-trip delay below 1 ms and 4% PID overshoot. Isolation Forest identified unusual operating points offline but was not validated for fault diagnosis. Among 25 matched responses, all five TEQ self-reported competency ratings increased significantly ( $p < 0.001$ ), while most SAQ and QRI responses were Good or Very Good.

Overall, REPAL supports portable automation, IoT/cloud monitoring and introductory anomaly detection. Future work should include multi-institution studies, practical and delayed assessment, MQTT/cloud timing, matched PID trials, labelled real-time anomaly tests and industrial pilot deployment.

Declaration of Generative AI in Scientific Writing

Generative AI tools were used only for language/readability enhancement, and the authors take full responsibility for the content of the manuscript.

|                      |                                  |
|----------------------|----------------------------------|
| <b>Nomenclatures</b> |                                  |
| $T_{max}$            | Maximum recorded temperature, °C |
| $T_{set}$            | Temperature setpoint, °C         |
| <b>Abbreviations</b> |                                  |
| AI                   | Artificial Intelligence          |

|       |                                                           |
|-------|-----------------------------------------------------------|
| AIoT  | Artificial Intelligence of Things                         |
| CM4   | Compute Module 4                                          |
| ICMP  | Internet Control Message Protocol                         |
| I/O   | Input/output                                              |
| IoT   | Internet of Things                                        |
| MQTT  | Message Queuing Telemetry Transport                       |
| PID   | Proportional-integral-derivative                          |
| PLC   | Programmable logic controller                             |
| QRI   | Questionnaire Regarding Improvement                       |
| REPAL | Research and Engineering Platform for Automation Learning |
| SAQ   | Self-Assessment Questionnaire                             |
| TEQ   | Teaching Evaluation Questionnaire                         |
| VFD   | Variable frequency drive                                  |

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