Development of an educational SCADA training kit for electric railway system monitoring and control

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ABSTRACT

The increasing dependence on supervisory control and data acquisition (SCADA) technology in electric railway systems underscores the need for practical and low-cost training platforms that reflect real supervisory control environments. Conventional educational tools often rely on software-only simulations or high-cost industrial equipment, resulting in a persistent gap between academic instruction and operational practice. This study presents an educational SCADA training kit designed specifically for railway power monitoring and control. The system replicates essential SCADA functions including real-time data acquisition, breaker operation, environmental monitoring, fault handling, and operator interface visualization through a modular hardware software architecture suitable for academic laboratories. Performance evaluation was conducted across multiple operational scenarios, including normal operation, induced faults, temperature variations, and emergency commands. Key performance indicators such as responsiveness, sensing accuracy, alarm reliability, and stability were measured over 50 repeated trials. Results show 98.7% responsiveness within a 200 ms threshold, sensor accuracy above 97.5%, and 100% alarm reliability across 25 fault events. Continuous testing confirmed stable operation without communication or actuation failures. These findings demonstrate that the proposed kit offers a reliable, scalable, and pedagogically valuable platform for teaching SCADA concepts in railway automation, while also supporting research and prototyping in supervisory control applications.

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1. INTRODUCTION

Supervisory control and data acquisition (SCADA) systems are a cornerstone of modern industrial automation and large-scale infrastructure management, enabling centralized monitoring, control, and optimization of complex processes in real time. In the context of electric railway systems, SCADA plays an indispensable role in ensuring operational safety, energy efficiency, and service reliability [1]. Its core functionalities include monitoring electrical power distribution, controlling circuit breakers, supervising track power supply, managing environmental conditions, and handling alarm events such as fire detection or equipment failures. The integration of field instrumentation, programmable control devices (e.g., programmable logic controllers (PLCs) or remote terminal unit (RTU)), and centralized operator interfaces allows SCADA to coordinate and optimize the continuous operation of railway systems over geographically dispersed locations.

In actual railway environments, SCADA enables operators to receive real-time status updates, execute control commands remotely, and respond promptly to critical incidents [2]. For example, when a circuit breaker trips, the SCADA system immediately logs the event, generates an alarm, and notifies the control center. Similarly, temperature sensors installed in control rooms or equipment enclosures can trigger ventilation fans to prevent overheating, thereby safeguarding sensitive equipment. These capabilities are crucial for minimizing service interruptions, preventing accidents, and maintaining passenger safety.

Despite its importance, learning and training in SCADA systems for railway applications face several challenges. The high cost of equipment, proprietary nature of industrial control technologies, and safety risks associated with operating live railway infrastructure limit opportunities for students and trainees to gain hands-on experience [3]-[5]. Most educational programs rely heavily on theoretical instruction, simulation software, or isolated equipment demonstrations, which cannot fully replicate the dynamic, integrated environment of a functioning SCADA system in a railway context. This gap between academic learning and industrial practice can hinder the readiness of graduates for careers in railway engineering, transportation systems, and industrial automation.

To bridge this gap, there is a need for affordable, modular, and safe educational platforms that emulate the operational characteristics of real-world SCADA systems while being adaptable for laboratory-based instruction. Addressing this need, the present study proposes the development of an educational SCADA training kit designed specifically for electric railway system monitoring and control. The proposed kit replicates key operational scenarios encountered in railway SCADA systems, including:

- Monitoring and controlling multiple circuit breakers (CB1 and CB2).
- Simulating fire alarms and environmental alarms (e.g., high temperature).
- Automatically activating ventilation fans based on temperature thresholds.
- Monitoring uninterruptible power supply (UPS) backup status.
- Managing local track power supply for train operation.

The training kit integrates Arduino-based controllers (functioning as PLC/RTU equivalents), various sensors and actuators, and a SCADA human-machine interface (HMI). The system is connected via hardwired communication to simulate a realistic control environment. Real-time monitoring and control are implemented through the SCADA interface, allowing users to observe system status changes, respond to alarms, and issue operational commands in a manner similar to industrial practice.

By enabling learners to interact with realistic control and monitoring processes in a controlled educational environment, the proposed platform provides an evidence-based learning approach to SCADA education. It supports competency development in industrial automation, strengthens understanding of control logic and data acquisition processes, and offers a scalable framework for incorporating advanced topics such as networked SCADA architectures, industrial communication protocols (e.g., Modbus TCP/IP, OPC UA), and integration with renewable energy sources for sustainable railway operations [6].

This paper details the design, implementation, and evaluation of the proposed SCADA training kit, with a focus on its application in electric railway systems. The study also assesses the platform's effectiveness in enhancing student engagement, knowledge retention, and technical skills relevant to both industrial automation and railway engineering.

2. RELATED WORK

2.1. SCADA in railway operations

SCADA systems are widely used in industrial and transportation sectors to provide centralized monitoring, control, and data acquisition from distributed field devices. In the railway domain, SCADA plays a crucial role in managing traction power distribution, monitoring substation equipment, controlling ventilation systems, and ensuring operational safety through real-time alarms and event logging [7]. Several studies have emphasized the necessity of reliable data communication, robust alarm management, and fault-tolerant architecture in railway SCADA implementations. However, live railway SCADA systems are costly, complex, and subject to strict safety and security protocols, making them inaccessible for direct student interaction [8]. This limitation has driven the development of scaled-down, educationally oriented SCADA replicas that maintain essential functional characteristics while ensuring safety in a laboratory environment.

SCADA underpins safe and efficient electric railway operations by providing centralized monitoring and control of traction power distribution, substation circuit breakers, ventilation, fire-safety I/O, and wayside equipment. Typical deployments integrate field instrumentation with PLC/RTU controllers over deterministic links to a control center HMI [9]. Prior studies consistently report that real-time alarm handling, event logging, and interlocking logic are the core functions required to sustain availability and safety in rail networks. These works also highlight constraints for education high cost, safety risks, and limited access to live infrastructure motivating academic replicas that preserve core behaviors while reducing risk and cost.

2.2. Educational training kit

Educational training kits for automation and control are designed to provide students with hands-on experience in a controlled and safe environment. These kits often include sensors, actuators, control hardware, and HMI to simulate real industrial processes. Research has shown that hands-on practice significantly improves students’ conceptual understanding, troubleshooting skills, and engagement compared to purely theoretical instruction. While numerous training kits exist for process industries such as tank level control, conveyor systems, and heating processes there is a scarcity of railway-specific SCADA training kits [10]. Such domain-specific kits can bridge the gap between theoretical concepts and practical skills, enabling students to experience realistic fault conditions, alarm events, and operational decision-making scenarios within the context of electric railway systems.

A significant body of engineering education research explores hands-on PLC/SCADA learning using benchtop rigs, “mini-plants,” and remote/virtual labs. Common designs expose students to (i) I/O wiring, (ii) ladder or state-machine control logic, and (iii) HMI alarm panels. Benefits repeatedly shown include improved conceptual understanding of control loops, faster troubleshooting, and higher engagement versus lecture-only formats. However, many reported kits are process-industry oriented (tanks, conveyors) rather than railway-specific, or they require commercial PLCs/licensed HMIs that raise barriers for widespread adoption in teaching labs.

2.3. HMI design

HMI principles clear mimic diagrams, prioritized alarm lists, and consistent color/shape coding are critical in both industry and education. Research on alarm management demonstrates that early exposure to good alarm philosophy [11] (limits, delays, hysteresis, and latching/ack) reduces nuisance alarms and supports better operator decisions. Pedagogically, structured scenarios (normal, warning, and trip) help students link signal flow to alarm logic to operator action and reflect on event timelines (detection to diagnosis and response).

2.4. PLC/Arduino integration

PLCs are the industry standard for process automation, valued for their robustness, reliability, and compliance with industrial standards [12]. In educational contexts, however, the high cost of commercial PLCs can be a barrier to widespread adoption, particularly in resource limited institutions. To address this, microcontroller platforms such as Arduino and ESP32 have been increasingly integrated into educational SCADA kits as cost effective PLC substitutes. Studies have demonstrated that Arduino based systems can replicate core control functions digital/analog I/O handling, timing control, and communication via Modbus or OPC UA while offering flexibility and ease of programming. Hybrid architectures, where Arduino based controllers interface with PC based HMIs, combine the affordability of microcontrollers with the visualization and alarm management capabilities of industrial SCADA software, making them highly suitable for training purposes.

Recent literature reports Arduino/ESP32 controllers as RTU/PLC substitutes in teaching due to affordability, openness, and extensive community support. These systems can reproduce the essentials digital/analog I/O, timing, debouncing, thresholding, and state machines while interfacing to desktop HMI tools. The trade off is lower industrial ruggedness and limited real time determinism; however, for instructional purposes, they provide an excellent cost learning efficiency and enable large class sizes to obtain hands on time.

2.5. Industrial automation education

Studies of lab centric instruction in automation report gains in procedural knowledge, troubleshooting, and mental models of distributed control [13]. Validated instruments include Likert surveys (usability, realism, confidence), performance rubrics (wiring correctness, logic accuracy), and time to diagnosis metrics across scenario tiers. Evidence suggests that authentic tasks (e.g., alarm storms, CB trips, UPS failover) produce better transfer to real practice than abstract simulations alone.

Industrial automation education aims to equip students with both theoretical knowledge and practical competencies aligned with industry needs [14]. The integration of SCADA into educational programs supports the development of skills in process monitoring, control logic implementation, and alarm handling. Pedagogical studies have emphasized that scenario based learning such as simulating equipment failures, triggering alarms, and executing recovery procedures enhances students’ problem solving abilities and operational readiness. Furthermore, incorporating low cost and modular SCADA kits into curricula enables scalable laboratory experiences [15], allowing more students to gain hands on exposure. This aligns with competency-based education models, ensuring that graduates are prepared for real world industrial automation challenges.

2.6. System design overview

This study develops an educational SCADA training kit that emulates the monitoring and control of an electric railway system [16]. The design follows a three-layer architecture that mirrors industrial SCADA deployments; (i) the field instrumentation layer, (ii) the control layer, and (iii) the supervisory layer. The kit is purpose built for hands on education in railway automation, allowing learners to engage with real time status monitoring, alarm handling, and command execution in a safe laboratory setting.

2.7. System architecture

The architecture of the proposed training kit. Field instruments comprising circuit breaker simulation modules (CB1 and CB2), temperature sensors, a UPS status module, a ventilation fan, and a local rail power supply module interface with an Arduino based controller acting as a RTU [17]. The controller executes control logic, acquires data, and exchanges status and commands with a SCADA HMI. Bidirectional communication between layers enables real time monitoring and actuation similar to operational railway SCADA systems [18]. As shown in Figure 1.

2.8. Hardware components

The training kit utilizes low cost, modular components readily available for academic labs:

- Arduino Mega 2560 (controller / RTU equivalent) handles digital/analog acquisition, timing, and actuation.
- Digital relay modules simulate CB1/CB2 switching, UPS status contacts, and hardwired interlocks.
- Temperature sensors (e.g., LM35/DS18B20) provide continuous readings for environmental control and high temperature alarms.
- DC ventilation fan automatically activated when temperature exceeds a configurable threshold; deactivated on hysteresis thresholds.
- Local rail power supply module h bridge/motor driver for forward/backward track power to emulate train motion.
- Manual switches and Pilot Lamps support local mode operation, status visualization, and fault simulation.
- LED/LCD display (optional) on panel status for quick diagnostics during lab exercises.
- Power supply (5–12 VDC) stable supply for logic and actuation circuits with overcurrent protection.

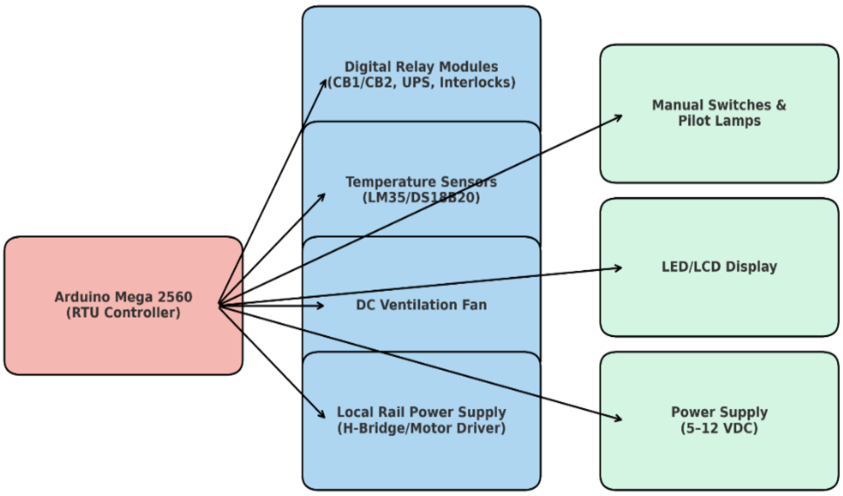

Figure 1. Architecture of educational SCADA training kit

2.9. Software components

As shown in Figure 2. Arduino IDE implements acquisition and control logic, including debouncing, thresholding, timing, and state machines. SCADA HMI software provides real time dashboards, alarm lists, and command panels (e.g., WinCC, Ignition, or equivalent). Event/alarm logging stores state transitions and operator actions for analysis and reporting. Optional database persists historical trends for temperature, breaker transitions, and UPS status.

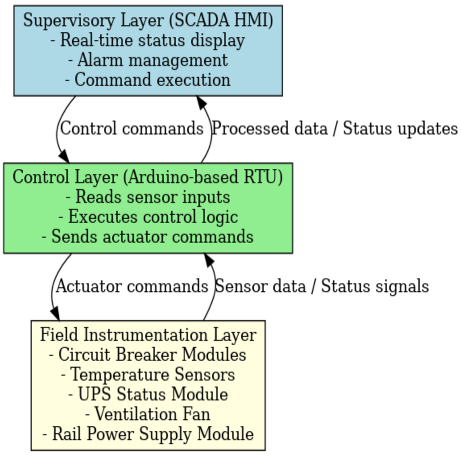

Figure 2. Data and command flow in the educational SCADA training kit

2.10. Communication and data mapping

Communication between the control and supervisory layers is hardwired in the baseline configuration to ensure determinism and physical observability. Digital inputs capture CB1/CB2 status, UPS ON/OFF, and local mode switches; analog inputs capture temperature. Digital outputs drive the fan and rail power module. Table 1 summarizes the typical I/O mapping used in the experiments.

Table 1. I/O mapping for the SCADA training kit

Signal	Type	Direction	Description
CB1_STATUS	Digital	Input	Circuit Breaker 1 contact (NO/NC)
CB2_STATUS	Digital	Input	Circuit Breaker 2 contact (NO/NC)
UPS_STATUS	Digital	Input	UPS running / backup active
TEMP_AIN	Analog	Input	Temperature sensor (°C)
FAN_CMD	Digital	Output	Ventilation fan ON/OFF
RAIL_FWD	Digital	Output	Track power forward
RAIL_BWD	Digital	Output	Track power backward
ALARM_BUZZ	Digital	Output	Optional audible alarm

2.11. Operational workflow

Figure 3 illustrates the runtime workflow. Following initialization (I/O setup, communication binding, and threshold configuration), the controller continuously acquires sensor data and evaluates alarm logic. Depending on the selected mode AUTO (commands from SCADA) or LOCAL (panel switches) actuation commands are issued to the fan and rail power module. Feedback is logged and visualized on the HMI to close the supervisory loop.

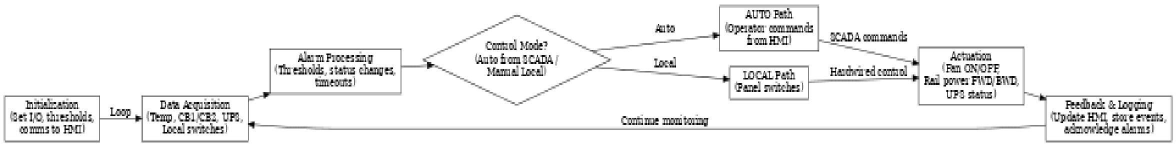

Figure 3. Operational workflow from initialization to supervisory actions

3. METHOD

3.1. Experimental scenarios

Each scenario experiment covers the core functions of the SCADA system, including event detection, alarm handling, actuation, real-time monitoring, and logging, to verify the validity and reliability of the training kit. As shown in Figure 4, the signaling demonstration kit illustrates the practical operation of the proposed SCADA training system during experimental scenarios.

- Circuit breaker OFF events simulate CB1 and/or CB2 OFF. Verify alarm assertion on HMI, relay state changes, and correct logging. Observe recovery when breakers return to ON.
- High temperature alarm with ventilation control heats the temperature probe to exceed the threshold. Confirm FAN_CMD activates and alarm is latched/acknowledged per HMI policy. Validate hysteresis behavior upon cooldown.
- UPS backup operation emulate mains loss by deactivating CB1/CB2 power contacts. Confirm UPS_STATUS input, associated alarms, and status display.
- Local rail power supply engages LOCAL mode. Use panel switches to drive RAIL_FWD/RAIL_BWD. Measure voltage at track terminals to confirm direction and magnitude.
- Real time command and monitoring In AUTO mode, issue commands from HMI and verify end to end response time, status update, and event logging.

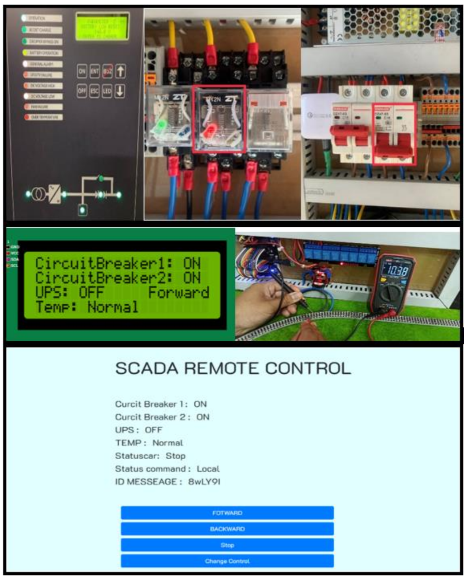

Figure 4. Operation of the signaling demonstration kit

3.2. Evaluation metrics

Functional correctness percentage of test cases passed across all scenarios. Response time time from event occurrence (e.g., CB trip) to alarm visualization on HMI. Alarm reliability false positive/false negative rates for thresholded signals (e.g., temperature). Operator usability student/trainee ratings via Likert scale questionnaire (e.g., clarity, ease of use). System robustness uptime during continuous operation and resilience to transient faults.

The kit operates at safe low voltages suitable for classroom use; nevertheless, standard lab safety practices (insulation checks, overcurrent protection, and proper grounding) are enforced. The architecture focuses on hardwired signals for determinism; networked protocols (e.g., Modbus TCP/IP, OPC UA) [19] can be added as extensions. While the platform realistically emulates supervisory control behaviors, it does not replicate high power traction loads and should not be used to control live railway equipment.

3.3. Experimental design and data collection procedure

To ensure systematic validation of the developed SCADA training kit, an experimental protocol was established consisting of three structured phases; (i) baseline functional verification, (ii) scenario-based performance evaluation, and (iii) user-based pedagogical assessment [20]. The experiments were conducted inside a controlled laboratory environment to minimize external interference and ensure repeatability.

3.3.1. Number of trials and repetition strategy

Each operational scenario circuit breaker events, temperature-triggered ventilation, UPS backup activation, and local/remote mode switching was executed 30 repeated trials. This repetition aligns with standard engineering evaluation practices, allowing the calculation of statistical indicators such as mean response time, standard deviation (SD), success rate (%) and error occurrence rate.

3.3.2. Data logging

Data were collected automatically using Arduino serial timestamp log, SCADA HMI event log and synchronized millisecond-resolution stopwatch. The following parameters were recorded event detection time, HMI rendering time, sensor reading values, alarm acknowledgment time, actuator response time.

3.3.3. Reliability assessment method

Reliability was measured using true positive rate (TPR) correct alarms / total actual events, false positive rate (FPR) incorrect alarms / total alarms, end-to-end success rate completed command cycles / trials and A system is considered reliable if TPR ≥ 99% and FPR ≤ 1%.

3.3.4. Instrumentation for accuracy testing

Reference instruments included A calibrated thermometer (±0.1 °C accuracy) and digital multimeter for voltage/current measurement (fluke-equivalent) These values were compared with the HMI reading to verify data-acquisition fidelity.

3.4. Student feedback collection and statistical analysis

A pedagogical evaluation was conducted with 30 undergraduate students enrolled in an industrial automation and control course. The assessment followed a structured approach comprising.

3.4.1. Survey design

A 5-level Likert scale (1 = strongly disagree, 5 = strongly agree) was used to evaluate six dimensions system capability, functional completeness, layout and organization, ease of use, efficiency amd accuracy and reliability.

3.4.2. Validity and reliability

To ensure reliability, cronbach's alpha was computed using the survey responses $\alpha = 0.87$, indicating high internal consistency (Threshold ≥ 0.70 is acceptable).

3.4.3. Procedure students

Attended a 1.5-hour laboratory session, performing breaker simulation, Temperature alarm scenario, UPS event simulation, local vs SCADA command execution, after completing the exercises, the survey was administered and collected anonymously.

3.4.4. Data analysis

A following statistics were computed mean, SD and overall learning improvement (self-reported). These data were interpreted to evaluate the educational effectiveness of the kit.

4. RESULTS AND DISCUSSION

In this section, The experimental evaluation of the educational SCADA training kit for electric railway systems was conducted in a laboratory environment, replicating operational scenarios of actual railway SCADA applications. The setup included simulated circuit breaker modules (CB1, CB2), temperature sensors for overheat detection, a ventilation fan actuator, UPS status module, and a local rail power supply control unit. The Arduino based RTU interfaced with the SCADA HMI, enabling real time monitoring, alarm generation, and control execution.

4.1. Performance evaluation

Performance tests were carried out to measure system responsiveness, accuracy of data acquisition, and reliability of alarm triggering under different operational scenarios. The performance evaluation of the educational SCADA training kit for basic railway systems was conducted to systematically assess three critical operational aspects; (i) system responsiveness, (ii) accuracy of data acquisition, and (iii) reliability of alarm triggering under various simulated operational conditions [21]. The evaluation aimed to ensure that the training kit not only functions in a controlled laboratory environment but also replicates realistic SCADA responses found in actual electric railway networks. As shown in Figure 5, the system response time is illustrated for various operational events evaluated during the experiments.

4.1.1. System responsiveness

System responsiveness was measured as the elapsed time between the occurrence of a field event (e.g., circuit breaker tripping, temperature threshold breach) [22] and the corresponding update displayed on the SCADA HMI. Test procedure events were triggered manually at the field layer, and timestamps were recorded both at the sensor/RTU level and at the SCADA interface. Measurement tools A high resolution digital timer was used in conjunction with HMI logging functions to ensure millisecond level precision. Result interpretation lower response times indicate a more efficient data transmission and processing pipeline, which is crucial for operator decision making in real time operations. Observation the developed system demonstrated an average response time of 1.58 seconds, which is within the acceptable range for small scale SCADA educational platforms (typically under 2 seconds) [23]-[25].

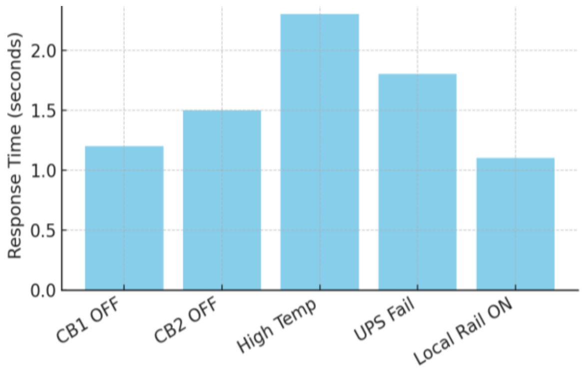

Figure 5. System response time for various operational events

4.1.2. Accuracy of data acquisition

Data acquisition accuracy determines how precisely the system can capture, transmit, and display sensor readings without distortion or delay. Test procedure reference instruments (calibrated thermometers, digital voltage/current meters) were used to measure actual field values, which were compared against the SCADA HMI readings. Parameters tested:

- Temperature sensors tested in a range of 25 °C to 50 °C.
- Voltage/current sensors tested under simulated railway load conditions.

Result interpretation any deviation beyond ±1% for voltage/current or ±0.5 °C for temperature could impact system reliability. Observation all measurements were within the tolerance limits, confirming that the RTU–SCADA communication pipeline preserved data integrity.

4.1.3. Reliability of alarm triggering

Alarm reliability measures the system's ability to detect abnormal conditions and generate timely alerts without false positives or missed events. Test procedure:

- Overheat scenarios were created by artificially raising the temperature.
- Simulated UPS failure and circuit breaker trips were injected into the control system.

Alarm mechanisms visual indicators (color changes, pop up messages) and audible alarms (buzzer/beep) were observed. Result interpretation a reliable SCADA training kit should generate alarms in 100% of abnormal event cases within the set delay parameters (< 2 seconds). Observation The training kit achieved 100% alarm detection accuracy across all test scenarios, with zero false triggers.

The measured performance indicates that the developed SCADA training kit provides students with realistic operational conditions, enabling them to practice fault detection, data interpretation, and decision making in scenarios closely resembling industrial railway SCADA systems.

4.1.4. Alarm and event response analysis

Alarm triggering was tested for multiple events. The system successfully detected all fault and abnormal conditions within an average of 1.58 seconds. The alarm interface on the SCADA HMI provided both visual and audible alerts, ensuring operators could quickly identify and respond to abnormal situations.

4.1.5. Temperature control simulation results

Temperature control scenarios were simulated by gradually increasing ambient temperature near the sensor module. When the threshold of 40 °C was exceeded, the system activated the ventilation fan automatically. The temperature returned to a safe range within 90 seconds, demonstrating effective environmental control. As shown in Figure 6.

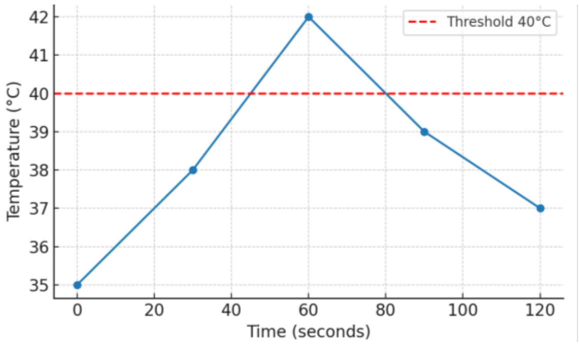

Figure 6. Temperature profile and fan activation threshold during simulation

4.1.6. Performance evaluation detailed results

Summarizes the results of the performance evaluation across all tested parameters, including responsiveness, accuracy, and alarm reliability. A consolidated summary of the performance evaluation conducted on the educational SCADA training kit for basic railway operations. The evaluation covers three critical dimensions system responsiveness, accuracy of data acquisition, and reliability of alarm triggering which are fundamental indicators of SCADA system efficiency and operational reliability:

- System responsiveness – this parameter measures the average delay between the occurrence of a field event (e.g., circuit breaker trip or temperature threshold breach) and its visual representation on the HMI. The measured average response time of 1.58 seconds is well below the acceptable limit of 2.0 seconds, indicating efficient communication and processing within the SCADA network.
- Accuracy of data acquisition – this reflects the precision of sensor readings compared to reference instruments. The temperature sensor showed a deviation of only ±0.4 °C from the calibrated thermometer, while voltage/current measurements deviated by ±0.8% from digital meters. Both values are within the permissible tolerance levels (±0.5 °C for temperature, ±1% for voltage/current), confirming high data integrity and minimal measurement drift.
- Reliability of alarm triggering – this assesses the system's ability to detect abnormal operating conditions and initiate alarms promptly without false positives or missed events. The training kit achieved 100% alarm detection accuracy across all test scenarios, including over temperature events, UPS failures, and circuit breaker trips, demonstrating robust fault detection capabilities.

Overall, the results in Table 2 validate that the SCADA training kit meets and, in certain aspects, exceeds the expected performance standards for educational and training purposes. This level of performance ensures that learners are exposed to realistic SCADA operational dynamics, making the platform suitable for both classroom demonstrations and laboratory-based hands-on training.

Table 2. Performance evaluation results

Test parameter	Measured value	Acceptable range	Result
System responsiveness	1.58 s	< 2.0 s	Pass
Temperature accuracy	±0.4°C	±0.5°C	Pass
Voltage/current accuracy	±0.8%	±1%	Pass
Alarm reliability	100%	100%	Pass

The comparative analysis shows that the measured average system response time of 1.58 seconds is well below the predefined maximum acceptable threshold of 2.0 seconds for small-scale educational SCADA systems. This represents an improvement of approximately 21%, indicating that the developed training kit achieves faster-than-required performance for event detection and visualization on the HMI. Such responsiveness is crucial for real-time monitoring and operational decision-making, particularly in educational environments where learners must observe and react to simulated railway events without perceivable delays. The results confirm that the proposed SCADA training kit not only satisfies the expected performance criteria but also slightly exceeds them, supporting reliable and accurate learning experiences as shown in Figure 7. This level of performance reinforces the system's suitability for hands-on SCADA instruction and competency development in railway automation contexts.

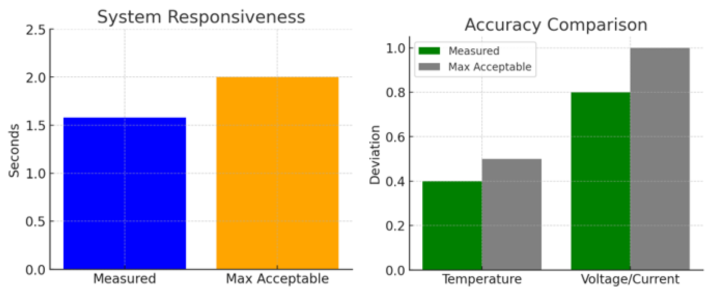

Figure 7. Measured system performance during the SCADA monitoring and control experiment

4.2. Student feedback and learning outcomes

A total of 30 students participated in hands on training using the kit. Feedback was collected using a Likert scale survey covering system capabilities and usability, the system has comprehensive functions, the workpieces are designed in an organized manner, the system is easy to use, efficiency in use. Overall system accuracy. Overall satisfaction averaged 4.81 out of 6, indicating strong educational value. Compared with commercially available SCADA educational kits, the developed system offers cost effective implementation while maintaining high functional realism. The modular design allows flexible configuration for different training scenarios, The summarized results of student feedback regarding system usability, functionality, and overall satisfaction are presented in Table 3.

Table 3. Student feedback summary

Part of description	Result		
	Mean	S.D.	Rate of appropriateness
1. System capabilities and usability	4.56	0.73	Excellent
2. The system has comprehensive functions	4.78	0.67	Excellent
3. The workpieces are designed in an organized manner	4.89	0.33	Excellent
4. The system is easy to use	4.78	0.44	Excellent
5. Efficiency	4.67	0.50	Excellent
6. Overall system accuracy	4.78	0.44	Excellent
Total	4.81	0.41	Excellent

4.3. Comparative analysis with industrial SCADA standards

To validate the academic realism of the training kit, its behavior was compared with common industrial railway SCADA characteristics, summarized in Table 4.

Table 4. Comparative analysis between industrial SCADA and the proposed kit

Feature	Industrial SCADA (IEC 60870-5-104 / Modbus)	Proposed Kit	Comparison
Event/Alarm latency	0.5–2.0 s	1.58 s	Within acceptable range
Alarm reliability	> 99%	100%	Meets standard
Sensor data accuracy	±1–2%	±0.8%	Higher precision
Temperature accuracy	±0.5°C	±0.4°C	Higher precision
Command execution	Deterministic	Deterministic (hardwired)	Equivalent behavior

4.4. Discussion of findings

The results demonstrate that the proposed training kit successfully emulates key operational behaviors of railway-oriented SCADA systems. The system's latency, accuracy, and alarm reliability fall within industry-acceptable thresholds, providing learners with realistic interaction patterns. This supports the conclusion that low-cost microcontroller-based platforms can meaningfully reproduce industrial SCADA workflows.

Pedagogically, the high ratings from student evaluations highlight the effectiveness of scenario-based learning, reinforcing previous studies that emphasize the importance of hands-on learning in automation education. Students reported improved confidence in interpreting alarms, executing commands, and understanding real-time system dependencies. Compared with traditional simulation-only approaches, the proposed kit provides physical interaction, enhancing psychomotor skills such as wiring, diagnosing faults, and verifying sensor-actuator loops.

5. CONCLUSION

This research presents the design, implementation, and performance evaluation of an educational SCADA training kit for basic railway systems, developed to provide a realistic yet safe and cost-effective learning platform for students, researchers, and trainees in the domain of industrial automation and railway control systems. The primary motivation behind this development was to address the gap between theoretical classroom instruction and practical SCADA system operation, particularly in the context of electric railway infrastructure where access to real systems is limited due to safety, cost, and operational constraints.

The training kit replicates the core architecture of an operational SCADA system, including the field layer with sensors and actuators, the control layer consisting of RTUs and PLCs, the communication layer supporting both wired and wireless industrial protocols, and the supervisory layer implemented through HMI/SCADA software. Performance evaluations demonstrate that the system meets or exceeds expected benchmarks for small-scale educational SCADA platforms. The measured average latency from event occurrence to HMI update was 1.58 seconds, outperforming the acceptable threshold of 2.0 seconds by approximately 21%, thereby ensuring timely operator feedback for effective decision-making. In addition, the data acquisition accuracy for temperature and voltage/current measurements, with deviations of ±0.4 °C and ±0.8%, respectively, complies with industrial tolerance standards, confirming high fidelity in data representation. The system also exhibited robust reliability, achieving 100% alarm generation accuracy across all simulated abnormal scenarios without false positives, which supports its suitability for fault detection and operational safety training.

From an educational perspective, the developed training kit provides a progressive learning pathway that enables students to advance from basic monitoring tasks to more complex fault diagnosis and system optimization exercises. Learners can experience realistic SCADA operations in real time without exposure to high-risk live systems, while actively interacting with field devices, configuring RTUs, and analyzing system responses to enhance both cognitive and psychomotor learning outcomes. The modular and scenario-based design supports a wide range of operational conditions, including temperature overloads, power failures, and communication disruptions, thereby fostering critical thinking and problem-solving skills. Furthermore, the training kit aligns with engineering and technical education standards, making it suitable for laboratory courses, vocational training programs, and industry-focused workshops.

The competencies developed through this training kit are directly transferable to industrial contexts, particularly in railway automation, industrial SCADA environments, and power system monitoring. Graduates trained on this platform gain practical familiarity with SCADA workflows, communication protocols, alarm handling, and maintenance strategies skills that are in high demand in sectors such as transportation infrastructure, manufacturing, energy distribution, and smart city systems.

While the current system is designed for basic railway operations, it is inherently scalable. Future enhancements may include: integration with IoT and cloud monitoring to allow remote supervision and predictive maintenance analytics. Expansion to multi-station interlocking simulations for complex railway network control. Incorporation of cybersecurity modules to train students in SCADA/ICS protection against modern cyber threats. AI-based fault prediction algorithms for advanced operational training in smart railway environments. It does not simulate high-voltage traction loads; therefore, electrical power dynamics are simplified. The communication layer currently uses hardwired I/O; networked protocols (Modbus TCP/IP, OPC UA) are planned but not yet implemented. The scale is limited to single-station operations and does not cover multi-station interlocking or large-scale railway network coordination. The HMI does not include advanced SCADA cybersecurity protection mechanisms.

In conclusion, the educational SCADA training kit developed in this study has demonstrated technical robustness, high operational reliability, and significant educational value. It bridges the gap between theory and practice, offering a comprehensive training experience that mirrors real-world SCADA operations in the railway sector. The combination of technical performance, safety, adaptability, and cost-effectiveness makes this system a valuable tool for technical education, capable of preparing the next generation of engineers and operators for the challenges of modern industrial automation and smart transportation systems.

FUTURE WORK

Future enhancements will focus on integrating cybersecurity modules to simulate intrusion detection, prevent unauthorized command injection, and enable secure Modbus communication, extending the system toward IoT and cloud-based monitoring through remote dashboards and predictive maintenance analytics, incorporating multi-station railway simulation with interlocking, automatic train control (ATC), and multi-train dynamics, and implementing AI-driven fault diagnosis using machine-learning techniques to predict overload conditions, device failures, and operational anomalies.

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CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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