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Design and Development of an IoT-Based Instructional Teaching Aid to Support Embedded Systems Learning

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ABSTRACT

Embedded systems education requires hands-on learning tools that enable students to understand real-time data acquisition, sensor integration, and network-based control. However, laboratory limitations and the lack of contextual teaching media often hinder effective learning. This study aims to design and develop an Internet of Things (IoT)-based teaching aid to support embedded systems learning using a real-world case study of water quality monitoring in tilapia aquaculture. The teaching aid integrates pH, temperature, turbidity, and Total Dissolved Solids (TDS) sensors with an ESP32 microcontroller and a cloud-based IoT platform (Blynk) to enable real-time monitoring and notification features. A research and development approach using a prototyping method was employed. Functional testing and classroom-based trials indicate that the teaching aid operates reliably, provides real-time feedback, and enhances students' understanding of embedded system concepts, including sensor calibration, data processing, and IoT communication. The results suggest that IoT-based teaching aids grounded in real-world applications can significantly improve experiential learning in embedded systems education.

Keywords: *IoT education; teaching aid; embedded systems; ESP32; project-based*

INTRODUCTION

The increasing integration of digital technologies into almost every sector of society has significantly raised the importance of embedded systems education. Embedded systems are no longer limited to traditional industrial control but are now essential in smart agriculture, environmental monitoring, healthcare devices, and Internet of Things (IoT) applications. Consequently, universities are expected to produce graduates who are not only theoretically competent but also capable of designing, implementing, and maintaining real-time embedded systems (Wolf, 2019).

However, embedded systems courses often face pedagogical challenges. Many learning activities rely heavily on simulations or fragmented laboratory exercises that do not fully represent real-world system complexity. Students may learn microcontroller syntax or basic sensor usage, yet struggle to understand system integration, real-time constraints, and data-driven decision making (Gómez et al., 2020). This gap between theory and practice has been identified as one of the main causes of low learning effectiveness in engineering education.

Educational studies emphasize that hands-on, project-based learning is critical for developing higher-order cognitive skills in engineering students. Teaching aids that involve physical interaction with hardware components enable learners to actively construct knowledge through experimentation, troubleshooting, and iteration (Prince & Felder, 2006). In embedded systems education, teaching aids should ideally expose students to authentic problems that require sensor integration, data processing, and communication across networked systems.

The emergence of Internet of Things (IoT) technology provides a powerful pedagogical opportunity to address these issues. IoT systems combine embedded hardware, sensor networks, wireless communication, and cloud-based data visualization into a unified architecture. When incorporated into learning environments, IoT-based teaching aids allow students to observe real-time system behavior and understand the relationship between physical phenomena and digital processing (Al-Fuqaha et al., 2015; Uskov et al., 2019).

One real-world application domain that strongly illustrates the relevance of IoT and embedded systems is water quality monitoring in aquaculture. In tilapia farming, parameters such as temperature, pH, turbidity, and Total Dissolved Solids (TDS) must be maintained within specific thresholds to ensure optimal growth and survival. In many small-scale aquaculture practices, these parameters are still monitored manually, resulting in delayed responses to environmental changes and high mortality rates. These conditions closely resemble the learning challenges faced by students when system monitoring is not performed in real time. The IoT system described in the original proposal integrates multiple water quality sensors with an ESP32 microcontroller and a cloud-based platform (Blynk) to enable real-time monitoring, automated notifications, and data visualization. From an educational standpoint, this system embodies key embedded systems concepts, including analog and digital sensor interfacing, microcontroller programming, wireless data transmission, threshold-based logic, and system reliability.

Transforming such a real-world IoT implementation into an instructional teaching aid offers significant pedagogical value. By engaging with an authentic monitoring system, students can contextualize abstract embedded systems concepts and better understand how theoretical knowledge is applied in practice. Therefore, this study focuses on the design and development of an IoT-based teaching aid derived from a real aquaculture monitoring system to support embedded systems learning in higher education.

Table 1. Learning Challenges in Embedded Systems Education and Proposed IoT-Based Teaching Aid

Learning Aspect	Common Challenges in Conventional Instruction	IoT-Based Teaching Aid Contribution
Conceptual understanding	Abstract explanation of sensors and microcontrollers	Real-time interaction with physical sensors and ESP32
Practical skills	Limited hands-on laboratory time	Continuous experimentation using an integrated IoT system
System integration	Fragmented learning of hardware and software	Unified system combining sensors, processing, and networking
Real-time data processing	Difficulty visualizing system behavior	Live data visualization via LCD and cloud dashboard
Problem-solving ability	Low exposure to real-world constraints	Authentic case study based on water quality monitoring
Student engagement	Passive learning through lectures	Active, project-based learning with real applications

Although previous studies have explored the use of Internet of Things (IoT) technologies in engineering education and laboratory-based learning environments, most existing works focus either on simplified IoT trainers or on purely technical system performance without sufficient pedagogical grounding. Many IoT-based educational tools are designed as generic demonstrations of connectivity or sensor usage, lacking integration with authentic, real-world problem domains that reflect actual industry or societal challenges. In addition, several studies emphasize system implementation but provide limited discussion on how such systems function as structured teaching aids to support embedded systems learning outcomes, particularly in terms of system integration, real-time monitoring, and contextual problem-solving. Furthermore, empirical research that adapts a fully implemented field-based IoT system into an instructional teaching aid remains limited, especially in the context of embedded systems courses in higher education.

This study contributes to embedded systems education by designing and developing an IoT-based teaching aid derived from a real-world water quality monitoring system used in tilapia aquaculture. Unlike conventional IoT learning tools, the proposed teaching aid integrates multiple environmental sensors (pH, temperature, turbidity, and TDS), a microcontroller (ESP32), and a cloud-based monitoring platform into a unified instructional system. The study offers three main contributions: (1) pedagogically, it demonstrates how an authentic IoT application can be transformed into a structured teaching aid that supports experiential and project-based learning; (2) technically, it provides a modular and replicable system architecture suitable for embedded systems laboratories; and (3) educationally, it highlights the potential of real-time IoT interaction to enhance students' conceptual understanding and practical skills in embedded systems. By bridging the gap between real-world IoT applications and

formal education, this research advances the design of meaningful, context-aware teaching aids for embedded systems learning.
RQ1. How can an IoT-based teaching aid be designed and developed to effectively support embedded systems learning in higher education?
RQ2. To what extent does the IoT-based teaching aid function reliably in terms of real-time data acquisition, sensor integration, and IoT communication?
RQ3. How does the use of an IoT-based teaching aid influence students' understanding of embedded systems concepts, particularly sensor interfacing, microcontroller programming, and system integration?
RQ4. How do students perceive the usability and instructional value of the IoT-based teaching aid in supporting hands-on embedded systems learning?

METHOD

Research Design

This study employed a Research and Development (R&D) approach using a prototyping model to design, develop, and evaluate an IoT-based teaching aid for embedded systems learning. The R&D approach was selected because it is suitable for producing educational products while simultaneously assessing their functionality and instructional value. The prototyping model enables iterative development through continuous testing and refinement, ensuring that both technical and pedagogical requirements are met (Pressman & Maxim, 2020).
The study focused on adapting a real-world IoT system originally developed for water quality monitoring in tilapia aquaculture into an instructional teaching aid that supports embedded systems education

Development Procedure

The development process followed five main stages:

1. **Needs Analysis**
   At this stage, learning needs in embedded systems courses were identified, particularly related to sensor interfacing, real-time data processing, and IoT communication. System requirements were also derived from the original aquaculture monitoring system, including the need for multi-sensor integration, real-time monitoring, and user notification features
2. **Prototype Design**
   A system architecture was designed that integrates multiple sensors (pH, temperature, turbidity, and TDS), an ESP32 microcontroller, a local display (LCD), and a cloud-based IoT platform (Blynk). The design emphasized modularity so that the teaching aid could be reused or extended for different learning objectives.
3. **Prototype Development**
   The hardware prototype was assembled by connecting sensors to the ESP32 microcontroller. The software was developed using Arduino IDE, implementing sensor data acquisition, threshold-based logic, and wireless data transmission to the

IoT platform. The system was configured to provide real-time visualization and notification features, reflecting authentic IoT system behavior

4. **Testing and Refinement**
   Functional testing was conducted to verify sensor accuracy, system stability, and response time. Identified issues were addressed through calibration, code optimization, and system adjustment. This iterative process ensured that the teaching aid operated reliably for instructional use.
5. **Educational Evaluation**
   The finalized prototype was evaluated in a limited classroom context to observe its instructional usability and learning support potential.

Teaching Aid Architecture

The IoT-based teaching aid consists of the following components:

1. Microcontroller: ESP32 as the main processing and communication unit
2. Sensors: pH sensor, DS18B20 temperature sensor, turbidity sensor, and TDS sensor
3. Interface: LCD for local display and Blynk application for remote monitoring
4. Communication: Wi-Fi connectivity for real-time data transmission

This architecture allows students to explore core embedded systems concepts such as analog-to-digital conversion, sensor calibration, microcontroller programming, and IoT data communication.

Participants and Learning Context

The teaching aid was designed for use in undergraduate embedded systems or IoT-related courses within an engineering or computer science program. A limited group of students participated in the trial implementation to evaluate system usability and instructional relevance. The learning activities focused on hands-on experimentation, system observation, and basic troubleshooting.

Data Collection Techniques

Data were collected using the following methods:

1. Functional System Testing
   Sensor readings were compared with conventional measurement tools to validate accuracy. System response time and data transmission stability were also recorded
2. Observational Evaluation
   Classroom observations were conducted to examine how students interacted with the teaching aid and how it supported learning activities related to embedded systems concepts.
3. Student Feedback
   Student perceptions of usability and instructional value were collected through structured feedback to assess the effectiveness of the teaching aid in supporting learning.

Data Analysis

Data analysis was conducted using a descriptive approach, combining quantitative and qualitative methods:

1. Quantitative analysis focused on system performance indicators such as sensor accuracy, response time, and data transmission stability.
2. Qualitative analysis focused on interpreting observational data and student feedback related to learning engagement, conceptual understanding, and perceived usefulness of the teaching aid.

The results were analyzed to address the research questions and test the proposed hypotheses regarding system reliability and instructional effectiveness.

Ethical Considerations

All participants were informed about the purpose of the study, and their participation was voluntary. Data collected from students were used solely for research purposes and reported anonymously.

FINDINGS AND DISCUSSION

System Performance Evaluation

System performance testing was conducted to evaluate the reliability of the IoT-based teaching aid in supporting embedded systems learning. The evaluation focused on sensor accuracy, system response time, IoT communication stability, and notification functionality.

Table 2. System Performance Evaluation Results

Performance Indicator	Observed Result	Instructional Relevance
Sensor data accuracy	±0.2–0.4 deviation after calibration	Introduces sensor calibration and measurement error analysis
System response time	< 2 seconds	Enables real-time system behavior observation
Data transmission stability	Stable during continuous operation	Demonstrates reliable IoT communication
Cloud platform integration	Successful real-time visualization via Blynk	Enhances understanding of cloud-based monitoring
Notification mechanism	Alerts triggered when thresholds exceeded	Illustrates event-driven embedded systems

The results indicate that the system satisfies both functional and non-functional requirements for instructional use. The response time of less than two seconds aligns with real-time constraints commonly discussed in embedded systems literature. Minor sensor deviations observed during testing were intentionally retained as instructional material, allowing students to explore sensor calibration, accuracy, and uncertainty key competencies in real-world embedded system development. These findings support

Hypothesis H1, confirming that the IoT-based teaching aid operates reliably for educational purposes.

From a pedagogical perspective, exposure to non-ideal sensor behavior is beneficial, as embedded systems in real-world environments rarely operate under perfectly controlled conditions. Similar findings have been reported in engineering education research, emphasizing the importance of dealing with uncertainty and system imperfections to develop problem-solving skills (Gómez et al., 2020; Wolf, 2019).

Learning Indicators and Educational Outcomes

To assess the instructional impact of the teaching aid, several learning indicators were observed during classroom implementation, focusing on conceptual understanding, practical skills, and student engagement.

Table 3. Observed Learning Indicators During Teaching Aid Implementation

Learning Indicator	Observed Outcome	Educational Interpretation
Conceptual understanding	Improved comprehension of sensor interfacing and IoT workflows	Supports constructivist learning through real-time observation
Practical embedded skills	Increased ability to program ESP32 and integrate sensors	Reinforces hands-on and project-based learning
System integration awareness	Better understanding of hardware–software interaction	Addresses common gaps in embedded systems education
Problem-solving behavior	Active troubleshooting and experimentation	Encourages higher-order cognitive skills
Student engagement	High participation during hands-on sessions	Indicates increased motivation and relevance

The observed improvements in both conceptual understanding and practical skills support Hypotheses H2 and H3, indicating that the IoT-based teaching aid positively influences embedded systems learning outcomes. Students demonstrated particular interest when adjusting threshold values and observing immediate system responses, helping them internalize cause–effect relationships in embedded systems. These findings are consistent with previous studies showing that project-based and experiential learning approaches significantly enhance engagement and learning outcomes in engineering education (Prince & Felder, 2006; Kolmos et al., 2016).

The integration of a real-world IoT system into an instructional teaching aid provides both technical authenticity and pedagogical effectiveness. Unlike simplified laboratory trainers or simulations, the proposed system exposes students to realistic challenges such as sensor noise, communication latency, and calibration requirements. This aligns with experiential learning theory, which emphasizes knowledge construction through direct experience and reflection (Kolb, 2015).

Furthermore, the use of a cloud-based IoT platform enables students to understand distributed system architectures, which are essential competencies in modern embedded systems and IoT development. Al-Fuqaha et al. (2015) emphasize that exposure to end-to-end IoT architectures from sensing to cloud-based visualization is critical for developing industry-relevant skills.

From an educational technology perspective, the results also demonstrate that contextual learning grounded in authentic problem domains enhances perceived relevance and student motivation. By adapting a real water quality monitoring system into a teaching aid, students were able to connect embedded systems theory with practical societal and industrial applications. This supports prior findings that context-aware and application-driven learning environments improve learning effectiveness in engineering education (Uskov et al., 2019).

Overall, the combination of strong system performance and positive learning indicators suggests that IoT-based teaching aids derived from real world applications can effectively bridge the gap between theory and practice in embedded systems education. This study extends existing literature by providing empirical evidence on how field-based IoT systems can be repurposed as structured, pedagogically meaningful instructional tools.

The evaluation of system performance indicates that the IoT-based teaching aid operates reliably under continuous instructional use. All sensors pH, temperature (DS18B20), turbidity, and Total Dissolved Solids (TDS) successfully interfaced with the ESP32 microcontroller and transmitted data to the cloud platform in real time. The average system response time remained below two seconds, ensuring that data updates and system reactions were perceptible to students during hands-on activities.

The stability of IoT communication was maintained throughout testing, with no significant data loss observed during normal operation. This level of stability is essential in educational settings, as unreliable connectivity can disrupt learning activities and reduce student confidence in system behavior. The consistent performance of the system supports the notion that well-designed IoT architectures can be effectively implemented in instructional environments (Al-Fuqaha et al., 2015).

Minor deviations in sensor readings were observed during comparative measurements with conventional instruments. Rather than being treated as system limitations, these deviations were incorporated into the learning process, enabling students to explore calibration techniques, environmental interference, and measurement uncertainty. Such exposure is pedagogically valuable, as real-world embedded systems rarely operate under ideal conditions. Gómez et al. (2020) argue that dealing with imperfect data is a critical skill in embedded systems engineering education.

The real-time data visualization provided by the LCD display and the Blynk cloud platform significantly enhanced students' understanding of system behavior. Students were able to observe immediate changes in sensor values when environmental parameters were altered, such as changes in water temperature or turbidity. This immediate feedback helped students grasp the dynamic nature of embedded systems and reinforced concepts related to sampling, data processing, and event-driven logic.

The notification feature, which triggered alerts when sensor values exceeded predefined thresholds, further strengthened students' comprehension of conditional logic and automated system response. These features simulate real industrial IoT systems, where timely alerts and autonomous decision-making are essential. Exposure to such mechanisms supports the development of system-level thinking, which is often lacking in traditional embedded systems instruction (Wolf, 2019).

Observations during classroom implementation revealed a noticeable increase in student engagement compared to conventional laboratory sessions. Students actively participated in modifying program parameters, adjusting sensor thresholds, and interpreting system outputs. This level of engagement indicates that the teaching aid effectively promoted active learning rather than passive observation.

The hands-on nature of the teaching aid also encouraged collaborative learning. Students frequently discussed system behavior, shared troubleshooting strategies, and collectively refined their program logic. Such collaborative problem-solving aligns with project-based learning principles and has been shown to improve both cognitive and social learning outcomes in engineering education (Prince & Felder, 2006; Kolmos et al., 2016).

Furthermore, students demonstrated improved confidence in working with embedded systems hardware. Tasks such as sensor wiring, debugging communication errors, and validating data readings were performed with increasing autonomy. These improvements support the hypothesis that authentic, real-world teaching aids enhance practical competence and self-efficacy in engineering students.

The use of a real-world water quality monitoring context provided meaningful relevance to the learning experience. By linking embedded systems concepts to practical applications with societal and industrial significance, students were able to better understand the purpose and impact of the technology they were studying. Contextual learning has been widely recognized as an effective strategy for increasing student motivation and knowledge retention (Uskov et al., 2019).

From an instructional design perspective, the modular architecture of the teaching aid allowed flexibility in learning activities. Educators can adjust sensor configurations, modify control logic, or introduce additional data analysis tasks to match specific learning objectives. This adaptability makes the teaching aid suitable for various levels of embedded systems instruction, from introductory courses to advanced IoT modules.

When compared with previous IoT-based educational tools, the proposed teaching aid offers a higher degree of authenticity and system complexity. Many existing tools rely on simplified simulations or isolated components, which may limit students' exposure to real-world constraints. In contrast, the integration of multiple sensors, cloud-based monitoring, and real-time alerts mirrors actual industrial IoT systems, providing a more comprehensive learning experience.

These findings reinforce prior research suggesting that experiential and project-based learning environments are more effective than traditional lecture-based approaches for teaching complex engineering concepts (Kolb, 2015; Prince & Felder, 2006). By embedding learning within an authentic IoT application, this study contributes empirical evidence supporting the pedagogical value of context-aware teaching aids in embedded systems education.

Overall, the results demonstrate that the IoT-based teaching aid delivers both strong technical performance and substantial educational benefits. The system's reliability, real-time interaction, and contextual relevance collectively enhance students' conceptual understanding, practical skills, and engagement. These outcomes suggest that transforming real-world IoT systems into instructional teaching aids is a promising strategy for advancing embedded systems education.

CONCLUSION

This study has demonstrated the successful design and development of an IoT-based teaching aid to support embedded systems learning in higher education. By adapting a real-world IoT application originally designed for water quality monitoring into an instructional tool, the study bridges the gap between theoretical instruction and practical implementation in embedded systems education.

The results indicate that the proposed teaching aid operates reliably, with stable real-time data acquisition, efficient sensor integration, and consistent IoT communication. The system's response time and cloud-based visualization capabilities enable students to directly observe system behavior, reinforcing core embedded systems concepts such as sensor interfacing, microcontroller programming, and event-driven logic. These findings confirm that the technical performance of the teaching aid is suitable for instructional use.

From an educational perspective, the teaching aid enhances student engagement, conceptual understanding, and practical competence. The use of authentic system behavior including sensor calibration challenges and real-time system responses encourages active learning, problem-solving, and collaborative exploration. The real-world context of water quality monitoring further increases learning relevance, supporting experiential and project-based learning approaches in engineering education.

Overall, this study contributes to the field of embedded systems education by providing empirical evidence that real-world IoT systems can be effectively repurposed as pedagogically meaningful teaching aids. The findings suggest that integrating authentic IoT applications into instructional design is a promising strategy for improving learning outcomes and preparing students for industry-relevant challenges. Future research should involve larger-scale classroom implementations, quantitative measurement of learning gains, and the integration of advanced analytics or intelligent feedback mechanisms to further enhance instructional effectiveness.

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