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A Secure Industrial Internet of Things (IIoT) Framework for Real-Time PI Control and Cloud-Integrated Industrial Monitoring

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ABSTRACT

The explosion of Industry 4.0 has augmented the demand for secure, agile, and real-time industrial monitoring and control applications. In this paper, a secure Industrial Internet of Things (IIoT) system for real-time PI control and cloud-based industrial monitoring is proposed. The developed system combines Siemens S-300 PLC (programmable logic controller) and Node-RED platform that provides real-time data acquisition, display, and remote control for industrial parameters like Level/Water temperature. An integrated end-to-end data pipeline is implemented to allow transparent information exchange between the PLC, Node-RED dashboard, MQTT-based services, and cloud infrastructures, providing real-time data synchronization as well as remote access. The PI controller, whose parameters can be adjusted online using a website or mobile app, is implemented by our framework without loss of control loop stability. Safety is improved by authentic access and the regulation of the user's rights in order to avoid undelegated system operation. The experimental validation in a real-world industrial automation lab reveals the robustness of the real-time monitoring, enabling concurrent visualization over multiple interfaces and satisfactory PI control performance. The results substantiate the efficiency, applicability, and reliability of the developed IIoT system for real-world industrial monitoring and control scenarios.

Keywords: Node-RED, IIoT, PLC S7-300, Real-Time PI Control, Cloud-Integrated Monitoring, MQTT, Industrial Automation, Secure IoT.

How to cite the article

1. Introduction

The rapid development of Industry 4.0 has extensively reformulated industrial automation through digitally enabled intelligent, integrated, and data-driven production systems [1–3]. Prior art ICS systems are concentrated around a point of presence monitoring and are overly manual, both to monitor and control the system. Cybersecurity will no doubt be of even greater concern across all industries, and as both OT (operational technology) and IT (information technology) systems are linked, there is an increased need for secure control solutions to ensure the protection of critical infrastructure [4–6].

Industrial Internet of Things (IIoT) is an important facilitator for this kind of integration, which can maintain quality process metrics in real time through the continuous collection/monitoring/cognitive control within the integrated distributed industry[7– 9]. IIoT links sensors, actuators, and programmable logic controllers (PLCs) to cloud-based platforms that increase operational transparency, minimize downtime, and drive better decision-making [10, 11]. Nonetheless, the PT respects have a heavy emphasis on data monitoring and analytics, sometimes neglecting to consider real-time control and security aspects, or considering them as secondary issues [12, 13]. Proportional–integral (PI) controllers are still commonly used for industry processes owing to the simplicity, robustness, and efficiency in controlling the important process variables such as temperature and liquid level [14]. Traditional PI-based con- trol systems need field parameterization and direct access to the control hardware, which adds complexity in maintenance and flexibility [15]. Combining IIoT platforms with PI control can facilitate remote parameter adjustments and online performance measurement, but its integration should be designed to not jeopardize the security of control stability as well as the system [16, 17].

In the past, studies discussed the use of IoT platforms, cloud services, and middleware solutions like Node-RED to improve industrial monitoring and automation. Although these methods show better data visualization and interoperability with other tools, most of them are based on simulation validation or do not have a full experimental evaluation on real industrial hardware. Additionally, security problems addressing unauthorized access, information integrity, and role-based control still represent a major obstacle for the mass deployment of IIoT in industrial setups. To bridge this gap, this paper presents a secure IIoT framework for online PI control and cloud-assisted industrial surveillance. The proposed system combined a Siemens S7-300 PLC with the Node-RED platform to achieve real-time measurement acquisition, multi-interface synchronous display, and PI controller parameter tuning from long distances. For secure communication between PLC-cloud, cloud-monitoring interfaces, and stability of the control loop, all data transmission is aggregated in a unified data pipeline. Unlike other methods, this solution is experimentally tested in an industrial automation laboratory, showing its practical viability and reliable system behavior. The main contributions of this paper can be summarized as follows:

• A secure IIoT architecture is being developed that will combine industrial control based on the PLC with cloud-enabled monitoring and analytics.
• Remote on-the-fly tuning of PI controllers is offered via Node-RED dashboards without the need for direct access to control hardware.
• An end-to-end data pipeline is built for synchronized monitoring over PLC HMI, web-based dashboards, and the cloud.
• Practical experimental verification is carried out on a Siemens S7-300 PLC installed in an industrial automation laboratory, and the results show a stable control performance and reliable data synchronization.

The remainder of this paper is organized as follows. Section 2 provides some related works in this paper. Section 3 describes the materials and methods, including the proposed IIoT framework architecture and communication mechanisms. Section 4 dis- cusses the experimental setup, experimental results, and system performance. Finally, Section 5 concludes the paper and outlines future research directions.

2. Related Works

The development of industrial automation systems based on IIoT has received more attention in recent years. There are large amount of research work related to IoT plat- forms for monitoring, visualization, and interoperability in industrial environments. However, how much real-time control, cloud integration, and security are considered jointly in the existing works is significantly different. Calderon et al. [18] present an IoT modular platform that combines the Elastic Stack tools with Apache Kafka for distributed edge–cloud architectures. We consider monitoring and visualization abilities and evaluate experimental results from sev- eral real-life use cases in terms of performance, scalability, and efficiency of system management. Zhao et al. [19] summarized a self-powered gait analysis system using TENGs with the capability for real-time step count and speed measurement. Such a system couples optimized electro spun nanofibers, signal conditioning circuits, and an IoT platform-based architecture with improved accuracy, reliability, and energy aspects in human motion monitoring. IIoT-based industrial surveillance and control system employing the ESP32, Blynk, and ESP-Now has been proposed by Hailan et al. [20]. This system can provide real-time sensor data monitoring, remote control, se- cure communication, and friendly visualization with more scalability, flexibility, and easier operation in both smart manufacturing domains. To allow real-time data acquisition and cloud-based analysis/visualization, an online industrial motor monitoring system is introduced based on IIoT in Sridhar et al. [21]. The solution enables predictive maintenance with advanced data analytics, secure information management, and an easy-to-use dashboard to boost motor reliability, cut downtime, and fire the boilers. Ushkov et al. [22] present an IIoT-enabled method for water quality monitoring and environmental protection. The device combines industrial sensors and MQTT protocol-based data propagation for instant visualization and analysis that illustrates efficient scalability in deployment, practical evaluation on water quality and filtration performance with IIoT platforms.

Unlike previous works, the present study introduces a secure and experimentally validated IIoT architecture that coalesces real-time PI control, cloud-based monitoring, and multi-interface access. The system developed herein provides a bridge between PLC-based control, Node-RED middleware, and secure cloud services within an integrated architecture that pushes the boundaries and brings to a practical level of development scalable and secure industrial IIoT deployments.

3. Methods and Materials

This section presents the proposed secure IIoT framework, which comprises system architecture, communication schemes, RTR strategy, as well as PI controller establishment and implemented attack defense mechanisms.

3.1 Proposed IIoT Framework Design

The developed solution delivers a secure IIoT environment for industrial real-time monitoring and PI-based control by integrating a Siemens S7-300 PLC within the Node-RED framework, cloud services, etc. The platform allows parameterization while the process is running, online visualization, remote operation, and safe data transfer over different interfaces. The PLC is interfaced with cloud storage, analytics services, and user interfaces by Node-RED as the core middleware. The PLC collects temperature and water level data from the industrial tank, and performs PI control strategies for deciding on whether to turn on/off the heater and pump. Such measurements are sent to Node-RED and processed, visualized, and sent downstream to the cloud. It is capable of bidirectional communication between the server and client. control parameters can be remotely updated. Figure 1 illustrates the overall architecture of the proposed IIoT framework, highlighting the interaction between hardware components, middleware, cloud services, and user interfaces.

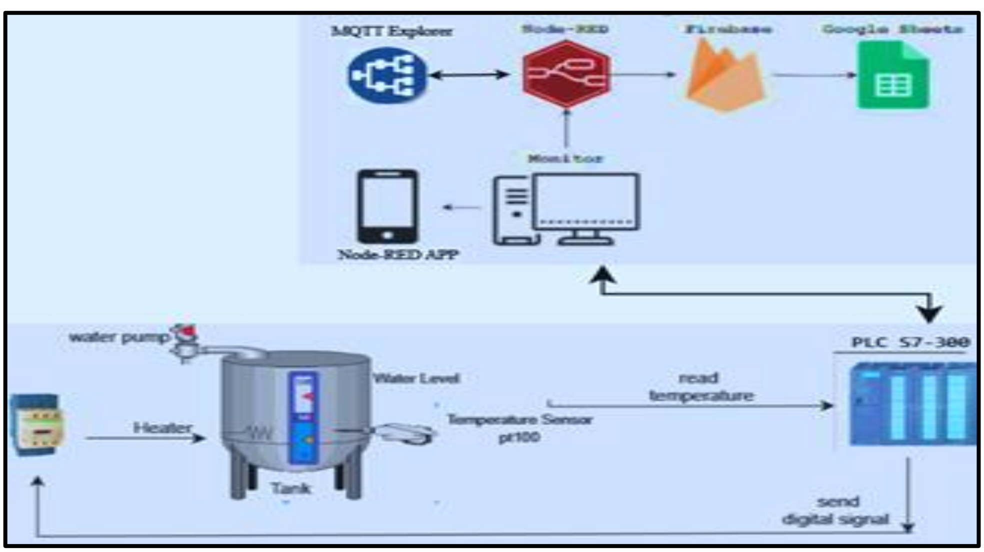

Figure 1. Proposed IIoT-based architecture for real-time industrial monitoring and remote PI control.

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3.2 Communication and Connectivity Architecture

Various industrial and IoT protocols are used for reliable and interoperable communication. Node-RED can communicate with the PLC S7-300 through industry communication interfaces. The real-time data exchange is supported between them. The MQTT protocol is also supported for lightweight, publish–subscribe communication between Node-RED and external clients and monitoring applications. A web-based dashboard is also offered for Node-RED to allow real-time presentation of process variables and PI controller parameter tuning remotely. Cloud connection is realized with Firebase for real-time data snapshot and Google Sheets for data analysis. The value of this layered communication system is validated with synchronized operation between PLC HMI, Node-RED dashboard, and cloud services, as shown in Figure 2.

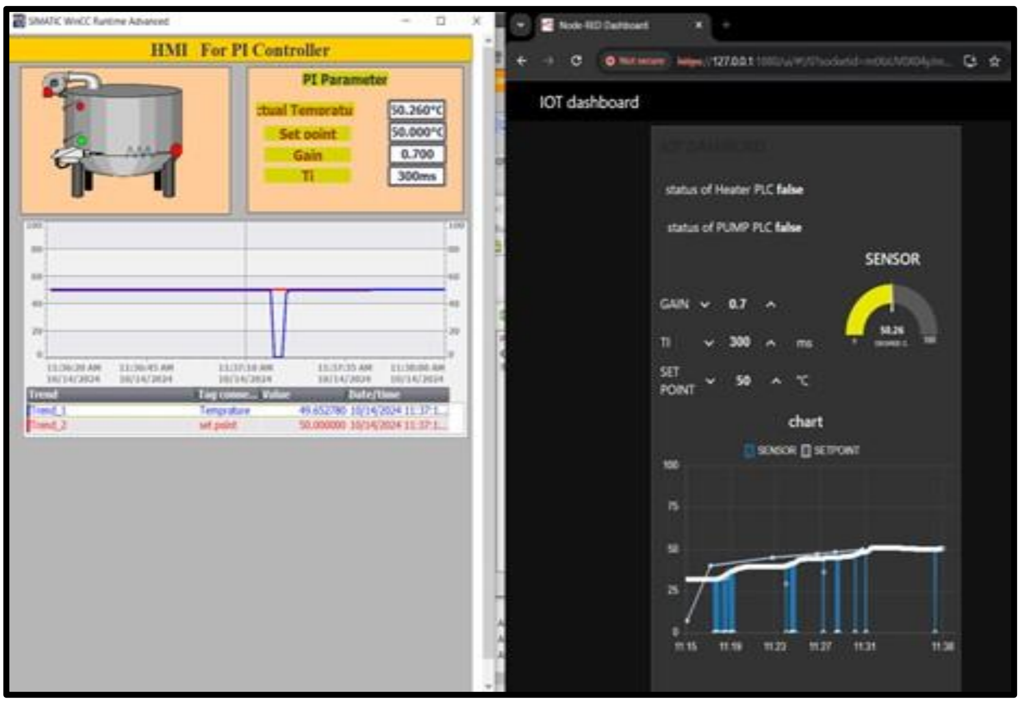

Figure 2. Node-RED dashboard interfacing with Simatic WINCC HMI to control and monitor real- time plant.

3.3 Real-Time Data Processing and Cloud Connections

Built to support flow-based programming, processing is done in real time by Node- RED. The procedure parameters passed on from the PLC can be visualized at the dashboard and concurrently sent out to the Firebase Real time Database for a cloud backup. Firebase allows data to be constantly synced without any user effort. The recorded data is automatically sent to Google Sheets through the Google Apps Script for organized visualization of historical analysis and performance assessment of the PI controller. The cloud-connected pipeline improves data legibility and helps to make decisions on both current time and past trends. The architecture of Firebase Real time Database for real-time storage and synchronization of industrial process parameters is presented in Figure 3. The database is connected to Node-RED, and data paths can be set up to feed temperature, water-level, PI controller parameters, and actuator status information directly from Node-RED. This architecture maintains progressive cloud synchronization and achieves secure storage with rapid access and convenient cross-interface data sharing without manual participation.

The Google Sheets interface used for real-time visualization and data analysis of industrial process information from Firebase is illustrated in Figure 4. By means of Google Apps Script, such parameters are automatically refreshed and stored in structured tables and charts. This interface enables comparison of measured values with controller set points in real time, enabling performance assessment of the PI control action as well as providing convenience for reading data to provide decision support.

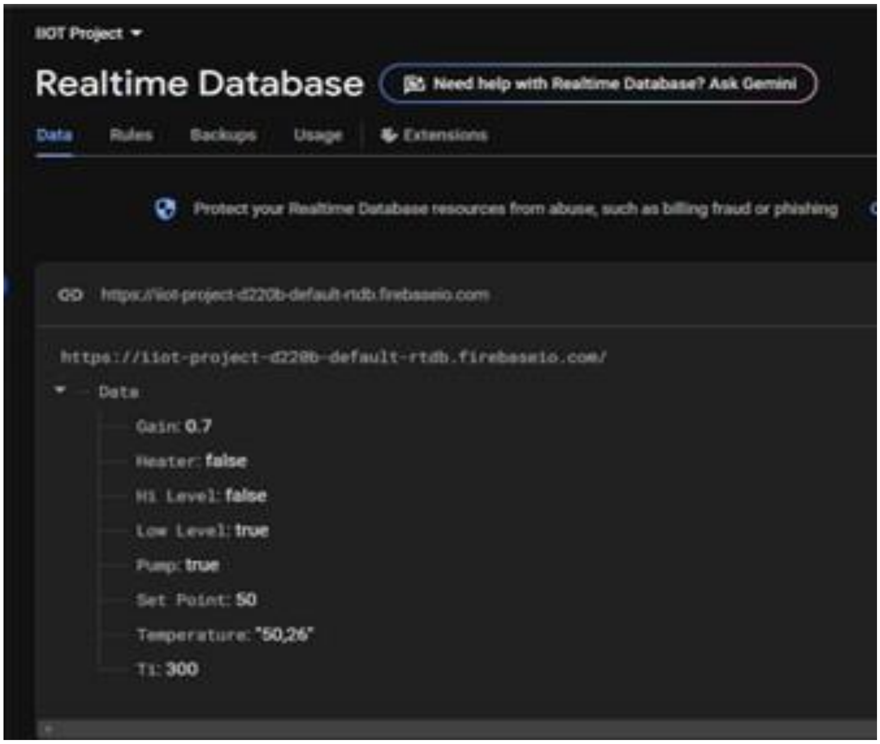

Figure 3. Firebase Realtime Database structure used for secure data synchronization.

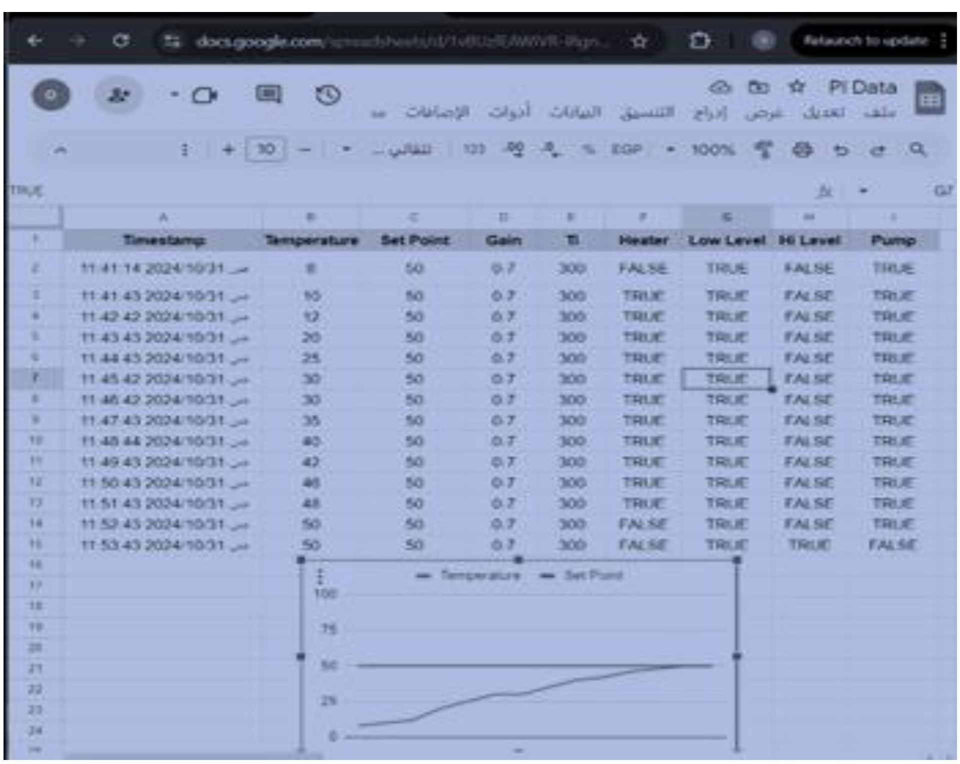

Figure 4. Google Sheets interface for real-time visualization and analysis of industrial process data.

3.4 Multi-Interface Monitoring and Remote Access

To improve the adaptability of the system, our architecture is designed to allow multi- interface access. The Node-RED dashboard can be accessed from web browsers and mobile devices for user interaction, while MQTT Explorer provides live data monitoring and two-way communication through MQTT. This is accomplished through tunneling methods, which permit authorized users to observe and manipulate the system from anywhere. This can achieve multi-platform compatibility, make the data uniform and consistent in each interface, and increase industrial application convenience. Real-time monitoring can be seen on MQTT Explorer, the PLC HMI, and the mobile dashboard in Figure 5.

Figure 5. Multi-Interface Monitoring (MQTT Explorer, Simatic WINCC HMI, and mobile dash board)

3.5 Data Flow Pipeline and Parameter Acquisition

The data acquisition is concentrated in the recovery of essential tank parameters, temperature, and water level. These parameters are collected by the PLC and sent to the cloud and user interface through Node-RED. It is the back and forth between BPiFC and LLF that provides real-time feedback and allows dynamic control parameter tuning. The entire data flow from sensing to cloud analytics and user interfaces is depicted in Figure 6, showcasing the ease and simplicity of our architecture.

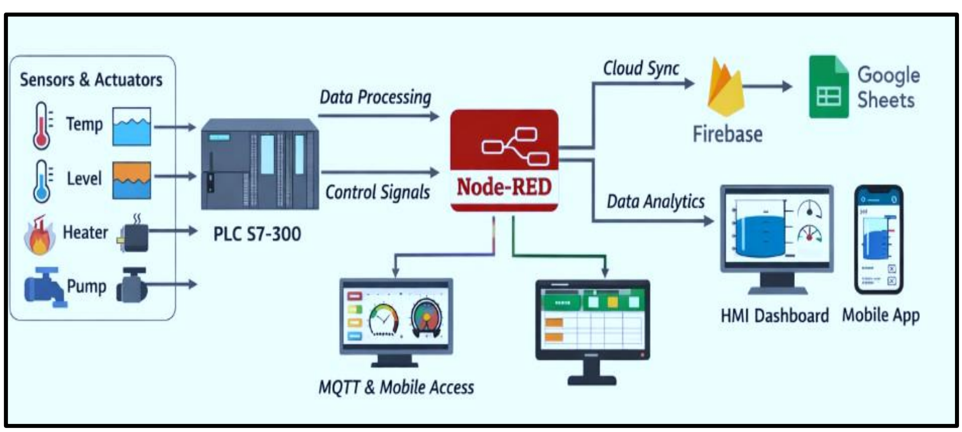

Figure 6. End-to-end data flow pipeline for monitoring and control in real-time.

3.6 PI Controller Parameter Control Mechanism

To control the tank temperature, we use a PI controller to regulate heater power following instantaneous feedback. Operation parameters, e.g., set point-value, proportional gain, and integral time (TI) the can be adjusted via remote on the Node-RED Dashboard. These values are sent to the PLC, where it runs the control logic and shifts actuator states. Such an approach allows for dynamic, responsive, and flexible control without having to directly access the control hardware. The control flow and data link are illustrated in Figure 7 between Node-RED and the PLC.

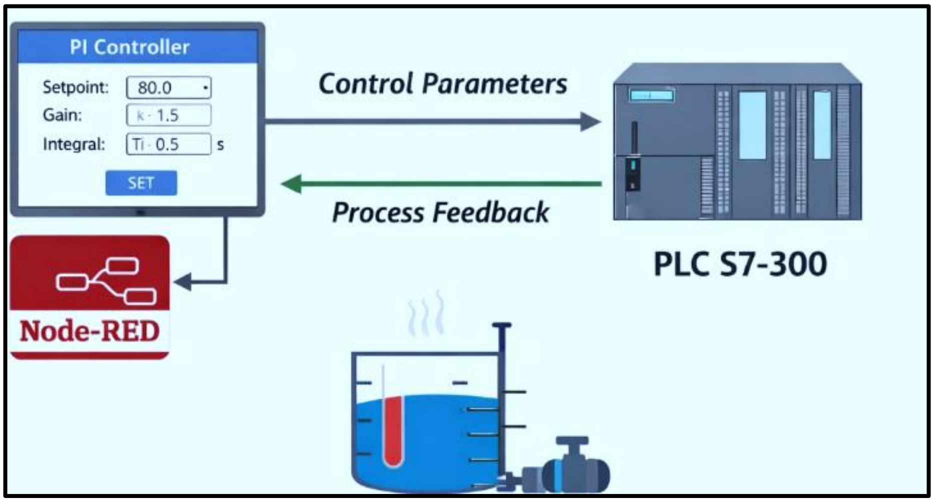

Figure 7. PI controller parameter control between Node-RED and PLC in real time.

4. Results and Discussion

In this section, we present the experimentation results in order to validate the secure IIoT framework for real-time PI control and cloud-based industrial monitoring. The practical implementation is tested in an industrial automation laboratory focusing on real-time data synchronization, control performance, and system reliability.

4.1 Real-time monitoring and control of the system

Figure 8 shows the experimental real-time performance visualization of active monitoring and controlling the proposed IIoT framework. The diagram represents a common display of process parameters on two separate computing systems, which are connected type writing isolated quant system. This is evidence of the consistent data collection and simultaneous monitoring from different interfaces. The Node-RED dashboards show real-time temperatures along with set point values and system status indicators, as well as live trend plots capturing ongoing data updates. The displayed values match for a bidirectional channel, both when using an Allen-Bradley S7-300 and Siemens S7-300 PLC, evidencing stable and reliable communication between the Node-RED middleware and connected cloud services. This synchronization highlights the fact that the PByIoT data flow pipeline is effective, and proves cloud integration does not add observable delay to or inconsistency in data.

4.2 PI Performance and Setpoint Tracking Control

As can be seen in Figure 8, the temperature response yields a smooth settling to the desired setpoint. A stable PI controller response is characterized by a relatively slow increase in the temperature curve without a substantial overshoot and oscillation. This validates that the proposed remote tuning of PI controller parameters in the Node-RED dashboard is practical and does not affect control stability. Real-time adjustment of setpoint, proportional gain, and integral time permits adaptive control response without any touch to the PLC hardware. The ability to perform these as well as other maintenance tasks in this fashion can be particularly advantageous, for example, when working “in-the-field” where manual manipulation or other labor-intensive interventions could add to out-of-service time or undesirable operational exposure.

Figure 8. Experimental results showing real-time monitoring, synchronized dashboards, and stable PI control performance of the proposed IIoT framework in the laboratory environment.

4.3 Reliability of Cloud-Based Data Processing

The experimental results are presented to show that the cloud based data synchronization runs reliably in conjunction with real-time control. Data sent from the PLC to Node-RED and then, in turn, forwarded to cloud-based services is consistent with the numbers displayed locally. This further verifies that the Firebase and cloud-based visualization integration does not affect the performance of the control loop. The system behavior confirms that the proposed architecture effectively decouples time-sensitive control responsibilities (handled by the PLC) from monitoring and analytics functions (performed in the cloud). This architectural division enhances system robustness and provides reliable performance in real-time scenarios.

4.4 Discussion and Practical Implications

The experimental results verify that the proposed IIoT framework can realize se- cure real-time industrial monitoring and control in a real laboratory environment. The proposed method, with respect to the traditional PLC-only systems, increases system flexibility for multi-interface access with remote parameter tuning and cloud- based online data analytics without changing the core control logic. In contrast with simulation-based studies, the results shown are obtained in real hardware integration and live system operation. The achieved stability, sync accuracy, and response time lead to the conclusion that the framework is applicable for short-range industrial automation also in smaller or medium scale. Moreover, the security mechanisms implemented in the system provide a fine-grained access to system resources conducting possible issues in IIoT scenarios.

5. Conclusion and Future Work

A secure IIoT environment was proposed in this article for real-time PI control and cloud-interconnected with industrial monitoring. The former system can achieve real- time data acquisition, visualization, and remote control by integrating S7-

300 that provided by Siemens, with Node-RED, which can meet the requirements of system reliability and security. A unified data pipeline was set up to facilitate the transfer of information between industrial equipment, cloud service, and multimodal monitoring platform. The experimental verification in an industrial automation lab found reliable real-time monitoring, synchronized viewing on multiple interfaces, and stable PI controller operation. The performances proved good setpoint following, smooth input response, and data synchronization between the PLC, the Node-RED dashboard, and cloud-integrated services. These results confirm the feasibility and effectiveness of the proposed method in practical industrial applications. The suggested IIoT platform in- creases operation flexibility due to more efficient off-site parameter tuning, the use of cloud data analysis, and secure access management without changing the pre-existing control logic. By decoupling the time-sensitive control functions from monitoring and analytics capabilities, the framework also enhances system scalability and minimizes disruptions. In summary, the proposed solution constitutes a practical and robust ba- sis for contemporary industrial monitoring and control systems, while scalability to more sophisticated industrial automation scenarios can be achieved.

In our future research, we will further develop the proposed IIoT-based framework to adapt with intelligent and self-tuning control methodologies implementing artificial intelligence (AI) and machine learning methods: tuning PI parameters automatically; predicting process optimization. Such an improvement would allow the system to dynamically adjust itself so as to cope with the changing working environments without human intervention. Another research direction is full-scale deployment in distributed industrial scenarios such as large production lines and multi-plant systems to study the scalability, network latency, and long-term reliability. The addition of edge computing functionalities is also foreseen to minimize communication delays and improve real-time decision-making. Moreover, we will investigate more advanced security measures by adopting intrusion detection (ID), as well as anomaly-based monitoring and blockchain-enabled trust management to better defend against unknown cyber threats. Finally, the framework can easily be augmented to accommodate more industrial protocols and heterogeneous devices, which makes interoperability more seamless and promotes ubiquitous application in various industrial automation.

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Contributions

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Ethics declarations
This article does not contain any studies with human participants or animals performed by any of the authors.

Consent for publication
Not applicable.

Competing interests
All authors declare no competing interests

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