

Development and Performance Evaluation of a PLC-Unity3D Sorting Conveyor Trainer Using FINS, Node-RED, and MQTT

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Abstrak

Perkembangan Industri 4.0 menuntut kompetensi yang melampaui penguasaan PLC konvensional, yaitu pemahaman sistem otomasi yang terintegrasi secara fisik dan virtual. Penelitian ini bertujuan untuk menjawab tantangan tersebut dengan merancang bangun sebuah trainer module untuk sistem sorting conveyor yang mengintegrasikan kontroler PLC fisik dengan representasi virtualnya berbasis Unity3D. Metode yang digunakan adalah menghubungkan PLC dengan virtual plant melalui arsitektur komunikasi FINS, Node-RED, dan MQTT untuk mencapai sinkronisasi real-time dalam simulasi penyortiran benda metal dan non-metal. Hasil pengujian menunjukkan sistem mampu mencapai akurasi penyortiran 95% pada kecepatan minimum conveyor dan 80% pada kecepatan maksimum conveyor, berdasarkan 20 percobaan untuk setiap kondisi. Pengujian latensi membuktikan bahwa sistem dapat berjalan mendekati real-time dengan total waktu tunda rata-rata dari PLC hingga aksi di Unity3D adalah 391,25ms. Selain itu, validasi kontrol analog menunjukkan adanya hubungan proporsional antara input potensiometer fisik dengan kecepatan conveyor virtual, membuktikan keberhasilan sistem ini sebagai media pembelajaran yang interaktif dan informatif.

Kata kunci: Trainer Modul, Virtual Plant, Conveyor, PLC, FINS Protocol, Unity3D

Abstract

The development of Industry 4.0 requires graduates to possess competencies beyond conventional PLC mastery, particularly in understanding physically and virtually integrated automation systems. This study addresses this by designing and developing a trainer module for a sorting conveyor system, integrating a physical PLC controller with its real-time virtual counterpart in Unity3D. The system utilizes a communication architecture combining the FINS protocol, Node-RED, and MQTT to ensure seamless connectivity. Performance evaluation showed sorting accuracies of 95% at minimum conveyor speed and 80% at maximum conveyor speed, based on 20 trials for each condition. Furthermore, latency testing confirmed its near real-time operation, with an average end-to-end delay of 391.25ms from the PLC to the virtual plant's response. These results validate the proposed system as a functional and representative training tool to support automation learning in the Industry 4.0 era.

Keywords: Trainer Modul, Virtual Plant, Conveyor, PLC, FINS Protocol, Unity3D

I. INTRODUCTION

Industrial automation, supported by control systems and information technology, has become a fundamental pillar of the manufacturing sector [1]. In response, the education sector is required to equip students with mechatronics competencies, where physical plants controlled by Programmable Logic Controllers (PLCs) serve as an important medium for workforce preparation [2], [3]. To meet the demands of Industry 4.0, engineering education must integrate automation technologies into curricula that emphasize practical problem-solving and system integration [4].

However, the transition toward Industry 4.0 requires PLC-based automation systems to extend beyond standalone control functions toward integrated systems involving physical processes, data exchange, and digital representations [5], [6]. This transition highlights a competency gap between understanding PLC programming logic and performing practical tasks in integrated automation environments [7]. Specifically, students need to develop competencies in electrical wiring and I/O connections, sensor and actuator verification, PLC program development, and communication troubleshooting between physical controllers and virtual systems. Conventional programming exercises or purely virtual simulations may not adequately address these competencies because they provide limited opportunities to inspect physical connections, diagnose hardware-related faults, or investigate communication delays and data exchange failures. Although virtual plants provide a safe and efficient simulation environment [8] and can overcome certain limitations of conventional training methods [9]–[11], practical interaction with physical automation components remains important for developing hardware-level troubleshooting skills [10], [14]. Interactive learning modules can also improve student engagement [12], [13]; however, the integration of physical control hardware and virtual plant simulation requires further attention in the design of automation training systems.

Although previous studies have investigated PLC-controlled virtual plants [15], [16], some approaches primarily emphasize PLC programming and virtual process visualization, while providing limited opportunities to work with physical sensors, actuators, and their associated electrical connections [9], [10]. This limitation may result in students understanding control logic without gaining sufficient experience in identifying wiring errors, verifying sensor responses, testing actuator operation, and troubleshooting communication between system components. These tasks are particularly relevant to mechatronics practice, where the performance of an automation system depends on the interaction between electrical hardware, control logic, and industrial communication [17]. Project-based learning can provide opportunities to develop these practical competencies through the integration and testing of physical systems [18].

To address this gap, this research designs, develops, and evaluates the technical feasibility of a sorting conveyor trainer integrated with a Unity3D virtual plant. The selected application represents a typical industrial sorting process in which sensor detection, PLC-based decision-making, and actuator control must operate in coordination [19], [20]. Accordingly, the trainer is designed to support several practical tasks: (1) wiring and verifying PLC input/output connections with physical sensors and actuators; (2) developing and testing PLC programs for object detection and sorting sequences; (3) checking sensor responses and actuator operation during functional testing; and (4) configuring and troubleshooting data communication between the PLC and the virtual plant. These tasks establish the practical requirements for the proposed system, including accessible physical I/O connections, a functional sensor–controller–actuator chain, observable sorting operations, and a communication interface that transfers PLC-related data to the virtual environment.

The contribution of this research is the implementation and performance evaluation of a physical sorting conveyor trainer integrated with a Unity3D virtual plant. Unlike approaches

that primarily focus on virtual process simulation or PLC–virtual plant integration, this system combines a physical OMRON CP1H PLC, object-detection sensors, and a pneumatic sorting actuator with a virtual representation through a communication architecture comprising FINS, Node-RED, and MQTT. The technical focus is to evaluate both the sorting performance of the physical system and the communication delay between the PLC and the virtual plant within the same experimental setup. The system achieved sorting accuracies of 95% at minimum conveyor speed and 80% at maximum conveyor speed, with an average end-to-end communication delay of 391.25 ms. These results provide a technical reference for physical–virtual integration in PLC-based automation training.

Table 1. Comparison of Previous Studies on Physical–Virtual Integration and PLC-Based Automation Training Systems

Study	Physical components and virtual plant	Communication architecture	Synchronization direction	Result	Process performance	Educational evaluation
Li et al. (2024) [21]	Physical PLC, I/O module, sensor module, and virtual industrial scene.	Factory I/O and MCGS warehouse simulation software are connected to the physical PLC.	Physical signals are acquired and processed for virtual observation.	PLC serial communication with MCGS and Factory I/O.	The study focuses on a semi-physical PLC practice-teaching system.	Practical teaching application of a three-dimensional warehouse.
Korpioksa (2014) [22]	PLC configurations using Omron CPM1, Omron CJ1M, and Beckhoff, connected to a Unity 3D model.	OPC server and socket server; OPC solutions included PLC Data Gateway and KEPServerEX 5.	PLC commands are sent to Unity; response-time measurement considers the signal path from Unity to the PLC and back.	Response times were measured in 50ms,	Drilling-station operation	Response time comparison between PLC Omron and Beckhoff's soft PLC for learning.
Villarroel et al. (2023) [23]	Siemens S7-1200 PLC for a virtual bottle-sealing plant in Unity 3D; SCADA implemented in InTouch.	Bidirectional TCP/IP Ethernet, OPC server, and a server–client architecture.	Bidirectional communication is explicitly reported between the physical and virtual parts.	Achieve an 83% score in the System Usability Scale (SUS)	A bottle-sealing process via a physical control panel with buttons and indicator lights.	Includes a usability test and discusses educational and engineering applications.
This study	OMRON CP1H PLC, physical sorting-conveyor trainer, and Unity3D virtual plant.	FINS, Node-RED, and MQTT broker.	PLC-to-virtual-plant bidirectional data transfer is evaluated; it describes how it sends control commands from	391.25 ms average end-to-end delay, from the PLC to the virtual plant	95% accuracy at minimum speed and 80% at maximum speed, based on 20 trials	Functional system validation as a technical reference for physical PLC and virtual plant

			Unity3D to the PLC.	response.	per condition.	integration training.
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The comparison in Table 1 highlights the differences between previous automation systems and the proposed sorting conveyor trainer. In particular, the comparison considers the integration of physical components with a virtual plant, the communication architecture, synchronization direction, result, process performance, and educational evaluation. The proposed system integrates an OMRON CP1H PLC with a Unity3D-based virtual plant through FINS, Node-RED, and MQTT, and evaluates both sorting accuracy and end-to-end communication latency. These aspects provide the basis for positioning the proposed trainer relative to previous work. The specific research gap should be established from the features and limitations documented in the reviewed studies.

2. METHODOLOGY

This research focuses on integrating a sorting conveyor trainer module with a virtual plant through a communication architecture that combines a PLC controller, the FINS protocol, Node-RED, and MQTT. The integration aims to enable data exchange between the physical controller and the virtual plant to support practical learning in industrial automation.

2.1 Research Framework

This research adopted the VDI 2206 guideline, a systematic design methodology for mechatronic systems. This framework was chosen because the project involves multiple integrated domains, including mechanical, electrical, and informatics systems. The process follows a V-model approach, encompassing stages from requirements analysis and system design to integration, verification, and validation.

2.2 System Requirements

The design was guided by a set of specific functional requirements. Mechanically, the project required the fabrication of a physical sorting conveyor equipped with a pneumatic cylinder as the sorting actuator and sensors capable of distinguishing metal from non-metal objects, which would then be represented as a 3D virtual plant. Electrically, the goal was to develop a portable trainer module to house the main PLC controller and integrate all physical I/O components, including push buttons, sensors, and motors, so they could be read and controlled by the PLC. From an informatics perspective, the core requirement was to achieve real-time, integrated operation between the physical and virtual plants, including an automated sorting mode where the pneumatic cylinder activates upon metal detection.

2.3 System Architecture and Communication Flow

The system architecture uses an OMRON CP1H PLC as the main controller for all physical inputs and outputs. To achieve real-time synchronization with the virtual plant, a specific communication architecture was implemented, as shown in Figure 1.

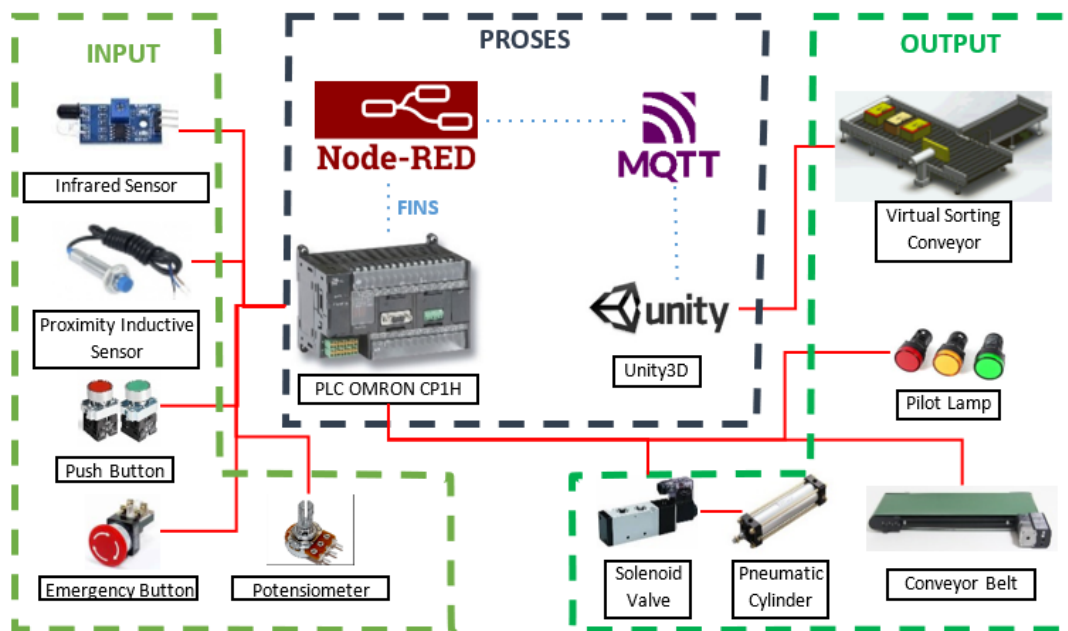


Figure 1 Overall System Architecture

The system architecture uses an OMRON CP1H PLC as the main controller for the physical inputs and outputs. Data are retrieved from the PLC memory using the FINS communication protocol, which provides command-based communication with OMRON controllers [24]. Node-RED serves as middleware to process and route the retrieved data through interconnected processing nodes [25]. The processed data are then published to an MQTT broker, from which the Unity3D application subscribes to the relevant messages to update the virtual conveyor. MQTT follows a client–server publish–subscribe messaging model that separates message publishers from subscribers [26]. The communication path implemented in this study is therefore PLC–FINS–Node-RED–MQTT broker–Unity3D.

For implementation, the OMRON CP1H PLC communicates with Node-RED through a direct Ethernet connection using the FINS protocol. Node-RED reads the required PLC memory addresses, particularly the CIO area, using a configured FINS-compatible node or software package. The retrieved data are processed and published to an MQTT broker using the configured topic. Unity3D subscribes to the topic and updates the corresponding virtual plant variables to represent the sorting conveyor operation. The system also supports bidirectional status communication to indicate successful connectivity between the PLC and Unity3D. The MQTT QoS level, broker address, communication port, and polling interval follow the actual system configuration. Once the communication is successfully connected, Unity3D sends a status signal through MQTT and Node-RED to the PLC, activating the connection indicator at CIO 100.05 when the connection is established.

This architecture facilitates a stable, two-way communication bridge between the physical controller and the virtual plant. A more detailed view of the communication stages between the software and hardware components is illustrated in Figure 2.

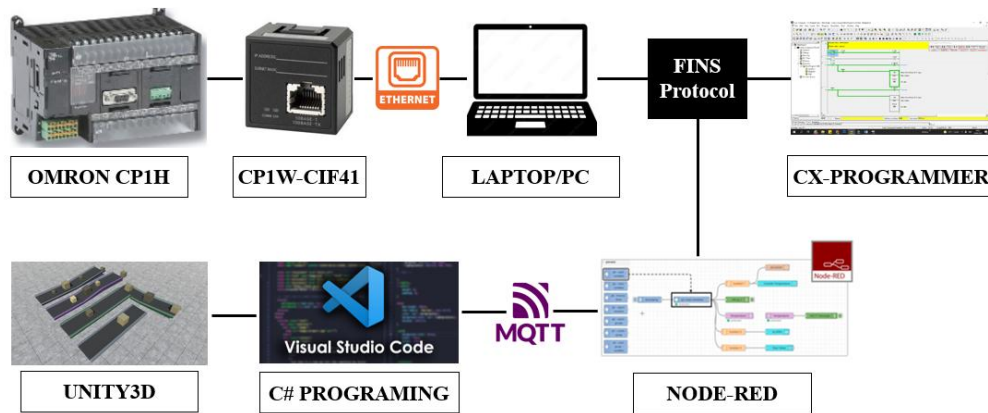


Figure 2 Design of Communication System between PLC and Unity3D

2.4 Verification and Validation Plan

To ensure the system met all requirements, a structured verification and validation plan was established. The verification phase focused on confirming the functionality of each communication link, including measuring the Round-Trip Time (RTT) between the PLC and Node-RED and ensuring reliable data transmission to Unity3D. The validation phase was designed to holistically test the integrated system against predefined success criteria, primarily focusing on quantitative parameters such as achieving a sorting accuracy of over 80% and maintaining functional and visual synchronization between the physical and virtual plants during operation.

3. RESULTS AND DISCUSSION

3.1 Implementation Results

Following the design and methodology, the physical and virtual plant of the system were successfully implemented. The trainer module was constructed as a portable, self-contained unit housed in a carrying case, as shown in Figure 3. The system's physical plant, consisting of the sorting conveyor, sensors, and pneumatic actuator, was assembled as a separate unit connected to the main trainer module via a dedicated control box, which is depicted in Figure 4.



Figure 3 The Embedded Trainer Module

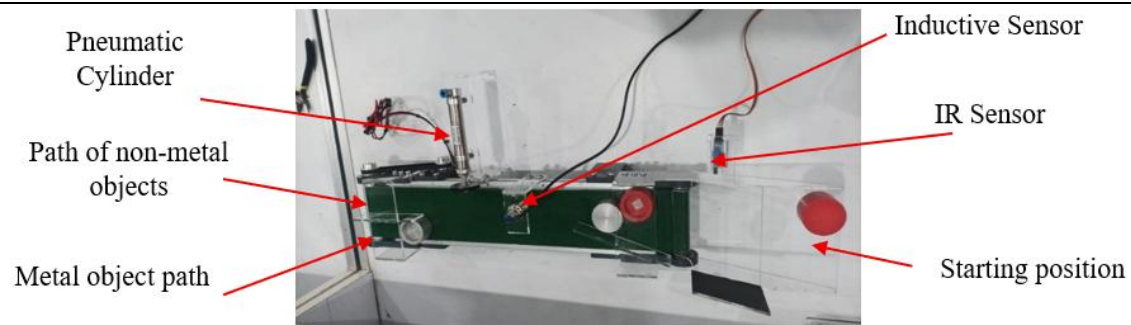


Figure 4 Installation of Physical Conveyor Mechanics (top view)

The virtual plant was developed in Unity3D as a digital twin representing the physical system's core functionalities. Although the virtual model was scaled 200:1 to ensure optimal rendering performance within the game engine, its functional mechanics, such as conveyor speed and sorting paths, were programmed to accurately mirror the physical counterpart. The final virtual environment is shown in Figure 5.

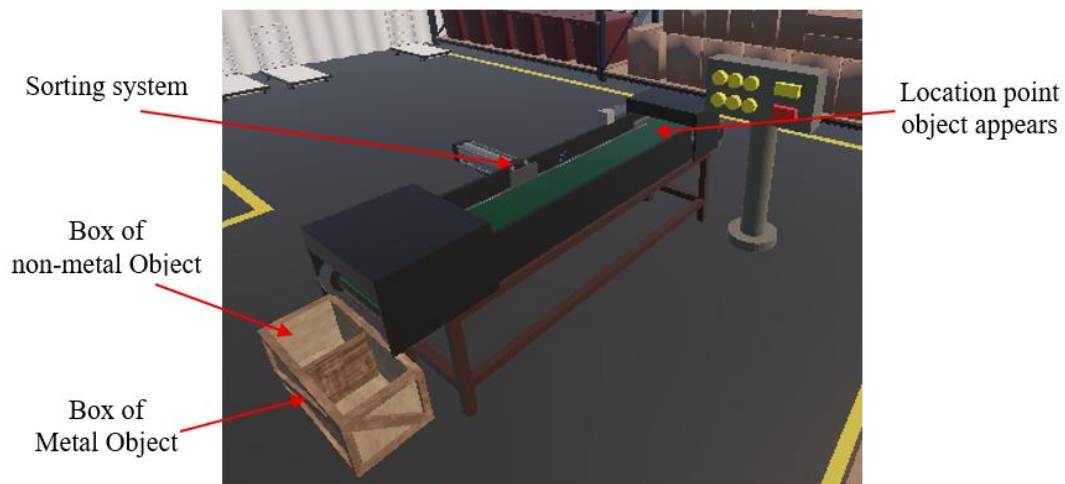


Figure 5 Design of Virtual Plant Integration in Unity3D

3.2 System Performance Evaluation

After successful implementation and integration, the system underwent a series of quantitative tests to validate its performance against the criteria established in the methodology. The evaluation focused on three key areas: communication latency, sorting accuracy, and analog control responsiveness.

3.2.1 Communication Latency

End-to-end communication latency, from a trigger at the PLC to the corresponding action in the Unity3D virtual plant, was systematically measured. The tests revealed an average total delay of 391.25ms. A breakdown of the latency components is presented in Figure 6. The analysis indicates that the largest portion of the delay occurred in the network segment between Node-RED and Unity3D via MQTT, whereas the PLC-to-Node-RED (FINS protocol) communication and internal Unity3D processing were significantly faster. This result confirms the system's ability to operate in near real-time.

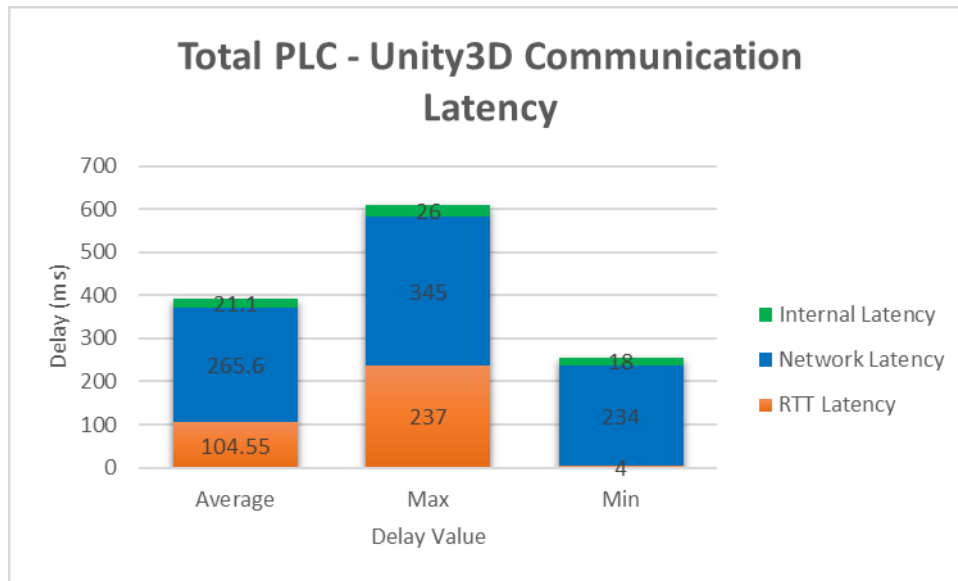


Figure 6 Total Communication Latency Breakdown (Average, Max, Min)

3.2.2 Sorting Accuracy

The system's functional accuracy was evaluated through sorting trials at both minimum and maximum conveyor speeds. The results, summarized in Table 1, show a high degree of reliability. At the lowest speed, the system achieved 95% accuracy, with only one error in 20 trials. At the highest speed, the accuracy was 80%. The increased error rate at higher speeds was attributed to the communication latency, which sometimes caused timing mismatches when objects were placed too closely together. Overall, the system met the predefined success criterion of over 80% accuracy.

The sorting accuracy was evaluated at minimum and maximum conveyor speeds, with 20 trials conducted under each condition. At minimum speed, the system achieved 95% accuracy, with 19 successful sorts and one error. At maximum speed, the accuracy decreased to 80%, with 16 successful sorts and four errors. These results indicate a reduction in sorting performance at higher conveyor speeds. The increased number of errors may be associated with communication latency and timing mismatches, particularly when objects are placed too closely together. However, the current results do not establish these factors as the sole causes of the errors. Furthermore, the limited number of trials introduces uncertainty into the estimated accuracy. Therefore, although the system demonstrated functional sorting capability at both tested speeds, further testing with more trials and controlled object spacing is necessary to establish its reliability under different operating conditions.

Table 2 Sorting Accuracy Test Results

Conveyor Speed	Trials	Successful Sorts	Errors	Accuracy	Approximation 95% confidence interval
Minimum	20	19	1	95%	76.4–99.1%
Maximum	20	16	4	80%	57.6–92.7%

Using the Wilson method[27], the approximate 95% confidence intervals for sorting accuracy were 76.4–99.1% at minimum speed and 57.6–92.7% at maximum speed. These relatively wide intervals reflect the uncertainty associated with the limited sample size of 20 trials per condition.

3.2.3 Analog Control Validation

The responsiveness of the analog control system was validated by comparing the physical potentiometer input, the PLC's PWM output signal, and the resulting virtual conveyor speed. The relationship between these three variables is plotted in Figure 7. The graph clearly illustrates a direct and highly consistent proportional relationship between the physical potentiometer's input (D100 Percentage) and the final virtual conveyor's speed (Conveyor Percentage). While the PLC's direct motor output (PWM Percentage) follows the general trend, it exhibits some deviation from the original input signal. In contrast, the near-real-time operation between the initial physical input and the final virtual output confirms that the data scaling logic implemented within the Unity3D script provides a more faithful and accurate representation. This visual evidence validates that the system can successfully translate physical user adjustments into a synchronized and responsive virtual action, a key requirement for an effective trainer module.

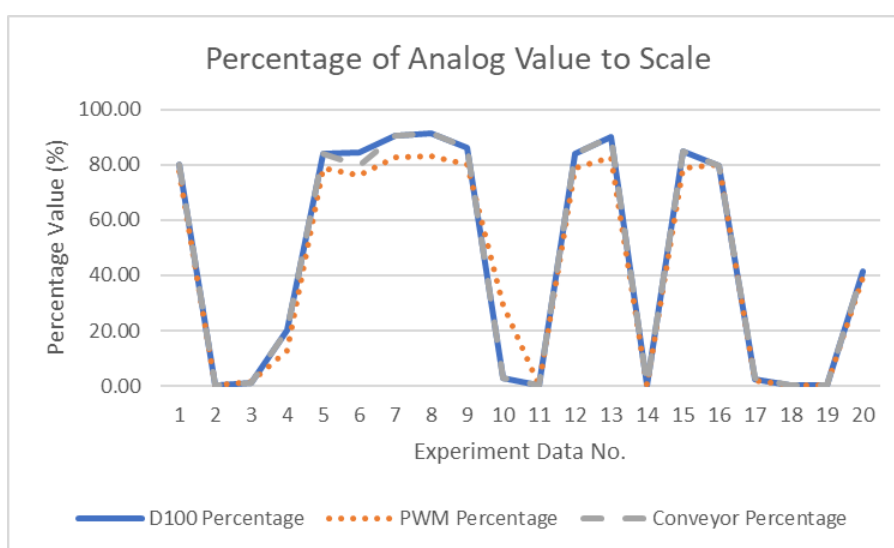


Figure 7 Comparison of the physical potentiometer input (D100 Percentage), the PLC's PWM output (PWM Percentage), and the virtual conveyor's speed (Conveyor Percentage), showing the correspondence between the input and virtual output.

4. CONCLUSION

This study demonstrated the integration of a physical sorting conveyor trainer with a Unity3D virtual plant using FINS, Node-RED, and MQTT. The system achieved sorting accuracies of 95% at minimum conveyor speed and 80% at maximum speed, with four sorting failures recorded in 20 trials at maximum speed. The average end-to-end delay from the PLC to the virtual plant response was 391.25 ms. These results demonstrate the system's functional capability under the tested conditions, although sorting performance decreased at higher conveyor speed. The measured delay indicates that communication between the physical and virtual systems was achieved, but does not establish seamless or real-time synchronization. Further evaluation under a wider range of operating conditions is required to characterize the system's performance more comprehensively.

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