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Development of Digital Twin Modeling for Smart Factory using OpenPLC-Based Control System

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Abstract

This research discusses how to design and develop Digital Twin modeling in a Smart Factory system with an OpenPLC-based control system. The main problems in conventional manufacturing systems are limited production line flexibility, difficulty in monitoring and controlling complex devices, and process visualization that is limited to technical data without a real depiction. Through the design of a laboratory-scale mechanical system, the creation of a control board based on an STM32H7 microcontroller with an OpenPLC platform, and the development of a Digital Twin application using Three.js and Node.js, this research produces a Smart Factory prototype that can be visualized in three dimensions and operated in real time via a local network or the internet. Test results show that the system is able to display sensor conditions, control actuators, and accelerate decision-making with shorter response times. The implementation of this system supports production process efficiency and offers an alternative industrial automation solution that is economical, flexible, and more intuitive in the implementation of digital transformation.

Keywords: *Digital Twin, OpenPLC, Control System, Industrial Automation, Visualization*

Abstrak

Penelitian ini membahas tentang bagaimana merancang dan mengembangkan permodelan Digital Twin pada sistem Smart Factory dengan sistem kontrol berbasis OpenPLC. Permasalahan utama dalam sistem manufaktur konvensional adalah keterbatasan fleksibilitas lini produksi, kesulitan pemantauan dan pengendalian perangkat yang kompleks, serta visualisasi proses yang terbatas pada data teknis tanpa gambaran nyata. Melalui perancangan sistem mekanik skala laboratorium, pembuatan papan kendali berbasis mikrokontroler STM32H7 dengan platform OpenPLC, serta pengembangan aplikasi Digital Twin menggunakan Three.js dan Node.js, penelitian ini menghasilkan prototipe Smart Factory yang dapat divisualisasikan secara tiga dimensi dan dioperasikan secara realtime melalui jaringan lokal maupun internet. Hasil pengujian menunjukkan bahwa sistem mampu menampilkan kondisi sensor, mengendalikan aktuator, serta mempercepat pengambilan keputusan dengan waktu respon lebih singkat. Implementasi sistem ini mendukung efisiensi proses produksi dan menawarkan alternatif solusi otomasi industri yang ekonomis, fleksibel dan lebih intutif dalam implementasi transformasi digital.

Keywords *Digital Twin, OpenPLC, Sistem Kontrol, Otomasi Industri, Visualisasi*

1. Introduction

The industrial transformation towards the Industry 4.0 era demands increasingly fast, flexible, and efficient production systems. Increasing product variety and shortening life cycles pose new challenges for the manufacturing industry, particularly in terms of production line flexibility, effective resource management, and speed of decision-making. In conventional manufacturing systems, production lines tend to lack adaptability, device monitoring and control become complex, and dashboards only display technical data without visualizing real-world conditions. These limitations have the potential to cause information delays and reduce production efficiency. One solution that can address these challenges is the implementation of a Digital Twin (DT), a three-dimensional virtual representation of a physical system that enables real-time two-way interaction, relevant to the development of the Internet of Things (IoT) and the integration of cyber-physical systems **[1].**

Several studies have discussed the use of DT in various fields. Biesinger et al. **[2]** developed a DT for production planning based on cyber-physical systems, while Soori et al. **[3]** reviewed the role of DT in improving sustainable manufacturing efficiency. Korkmaz **[4]** provided a technical overview of DT developments in smart manufacturing, while Guerra-Zubiaga et al. **[5]** discusses the development approach of DT for industrial automation systems through manufacturing case studies. These studies demonstrate the potential of DT to improve production precision, although its implementation still faces limitations in terms of interactivity and system integration.

On the control technology side, several studies highlight the use of OpenPLC as an alternative to open-source industrial controllers. Fujita et al. **[6]** built an OpenPLC-based control system testbed for security testing, while Lazaridis et al. **[7]** explored securing Modbus TCP communications using OpenPLC and Factory IO. Hubacz & Trybus **[8]** developed a dual-core PLC architecture to improve control system performance. Koulouris et al. **[9]** applied DT to the food industry for production simulation and scheduling, demonstrating its flexibility in supporting manufacturing processes.

Furthermore, Martinez-Ruedas et al. **[10]** integrated DT with 3D SCADA for real-time monitoring of an olive oil factory. The results of this study demonstrate that integrating DT with visualization and control systems can accelerate decision-making and improve operational efficiency. However, most research is still limited to simple and less interactive visualizations, and does not fully support direct control of physical systems. Therefore, this study proposes the development of a Digital Twin prototype in a Smart Factory integrated with an OpenPLC-based control system as a more flexible, economical automation solution and a more intuitive implementation of monitoring and control systems.

2. Method

Control systems in the manufacturing industry generally utilize Programmable Logic Controllers (PLCs) and Human Machine Interfaces (HMIs), which are relatively expensive and often imported. Furthermore, these systems use two-dimensional (flat) displays, which are considered inadequate representations of actual physical systems **[11-12].** DT has been applied in the food processing industry **[13]** and for big data variance analysis [14] but is still visualized using only illustrations and block diagrams. In the olive oil mill industry, DT is combined with real-time SCADA **[15],** but this requires extensive hardware and development tools. These studies generally suffer from shortcomings, including limited visualization and a lack of real-time two-way interaction.

The novelty of the DT application in this research lies in the 3D interaction and visualization that represents actual activities, including status, indicators, and physical movements of mechanical elements. Besides being more intuitive and aesthetically pleasing, this DT can be explored with more flexible 3D navigation (zooming, panning, rotating).

Microcontroller systems have been extensively studied and implemented **[16-18].** The low-power microcontroller used in this study still has speed limitations (16...48MHz). The use of Raspberry Pi as a PLC has also been studied **[19].** In addition to being relatively more expensive than microcontrollers, Raspberry Pi also requires boot time when activated. In general, OpenPLC performance depends on the processor used **[21].** This study has limitations, namely relatively low speed and a minimal number of inputs/outputs. The novelty in the control system developed in this study is the use of an STM32H7 microcontroller with a speed of 500MHz equipped with digital I/O interfaces, analog I/O, and data communication standards that are ready to connect to network systems (HTTP, MQTT, websocket and TCP/IP). This microcontroller has an instant boot time (hundreds of milliseconds) compared to single board computers (SBCs) such as Raspberry Pi, which have boot times reaching tens of seconds.

This research methodology (Figure 1) was designed to produce a prototype Digital Twin system integrated with a laboratory-scale Smart Factory. The research stages were carried out systematically, starting with needs analysis, system design, hardware and software development, and integration and testing.

a) Requirement Analysis

The initial stage of the research was identifying the requirements for the system to be built. The designed system consists of three main components: a mechanical system, an electronic/control system, and a Digital Twin application. In this research, the development focus was directed at processing station equipped with conveyors, sensors, actuators, linear axes, and grippers to simulate production activities.

b) System Design

Based on the identified needs, the system design included (i) the mechanical system development, (ii) the electrical and control system development, (iii) the Digital Tin application development.

c) System Integration

The three system components are integrated through a communication network based on industry-standard protocols (TCP/IP, MQTT, and WebSocket). Integration is achieved by connecting the control board to the sensors and actuators, while also connecting them to the Digital Twin application via a server.

d) System Testing

Testing is conducted to ensure the prototype's performance meets the established success indicators: the control board can read sensors and activate actuators, the control board can send and receive data to/from the server, the mechanical system can operate according to the specified sequence, the Digital Twin application can visualize system conditions in real time, and the application can control actuators through a 3D display.

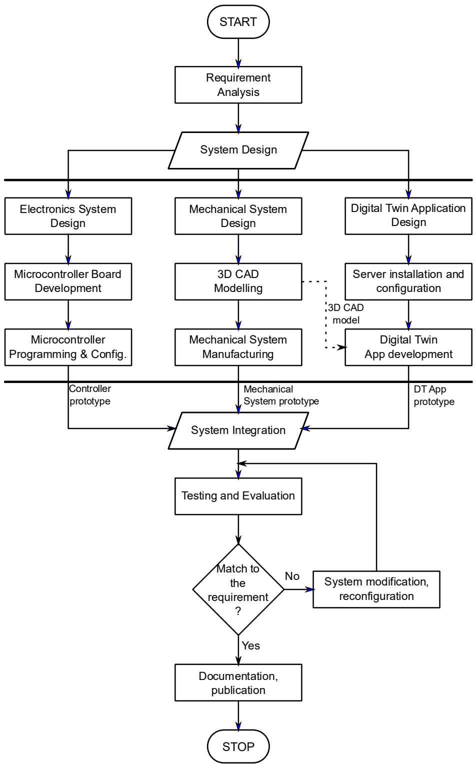

Figure 1. Flow chart of research methodology

2. Research implementation

The research focused on a processing station with mini conveyor components, sensors, pneumatic actuators, a linear axis, and a gripper (Figure 2). Identification of these requirements served as the basis for determining the mechanical and control design. The system design is divided into several sections based on their respective fields: mechanical systems, electronic systems, and Digital Twin applications. The mechanical system was realized using an aluminum profile as the frame, a mini conveyor with a DC motor, and pneumatic actuators for gripper and linear axis movement. An proximity sensor was installed at the end of the conveyor to detect the presence of workpieces.

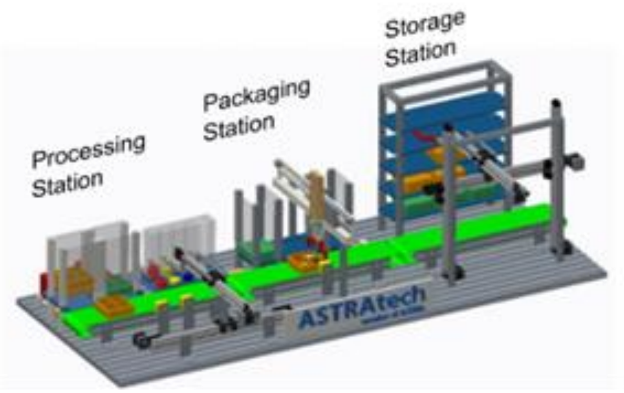

Figure 2. Initial Smart Factory Mechanical System Design

Digital Twin application was developed using Three.js and Node.js to display system conditions in interactive 3D. Figure 3 shows the block diagram of the software and communication system. The application displays sensor status and actuator conditions, as well as provide manual control of the conveyor, gripper, and pneumatic actuator.

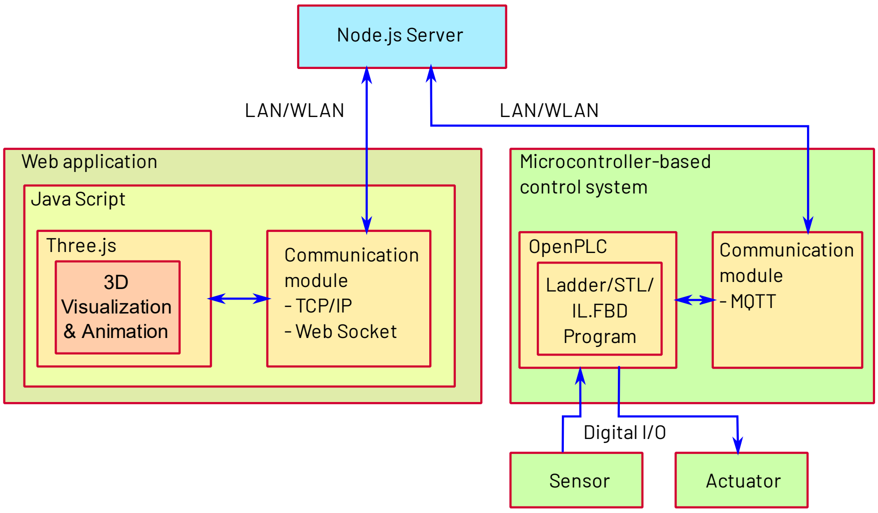

Figure 3. Block diagram of control system design

After the design phase was completed, the system development process was carried out to realize the design.

a. Mechanical System Development

The mechanical system frame was constructed using aluminum profiles assembled according to the CAD design. The mini conveyor was fitted with a 12V DC motor, while the pneumatic actuator was positioned to drive the gripper and linear axis. Displacement sensors were placed on the conveyor line to detect the presence of the workpiece.

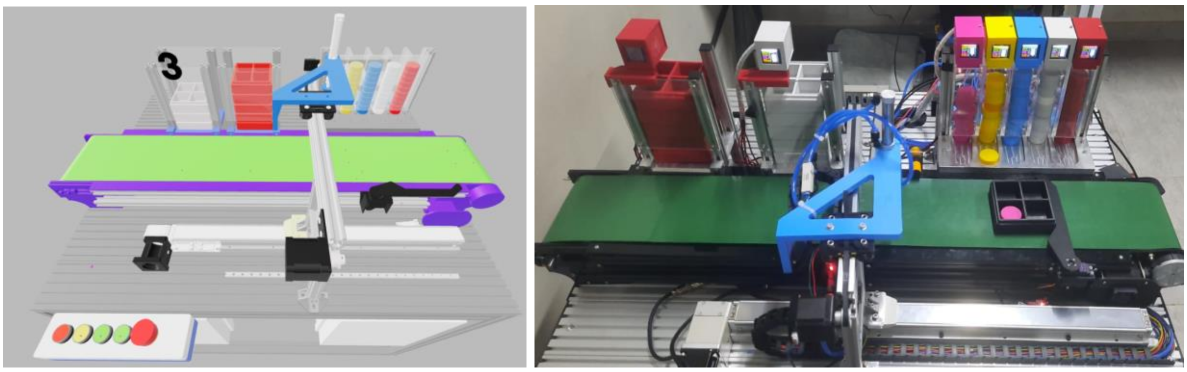

Figure 4. Three.js-based Digital Twin application and physical system.

b. Electronic/Control System Development

The developed electronic/control system consists of an STM32H7 microcontroller-based control board programmed with OpenPLC. This board reads sensors, executes control logic, and controls actuators. The input/output circuits are connected via digital I/O modules, while data communication is conducted via the TCP/IP protocol (Figure 5).

An STM32H7-based control board is installed on the main control module. Sensor inputs and actuator outputs are connected via I/O terminals. Basic logic programming is performed using the OpenPLC platform to ensure the actuators operate according to the control signals.

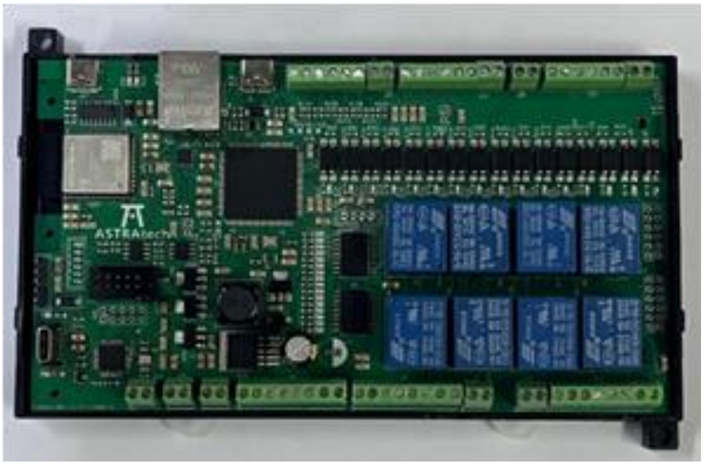

Figure 4. STM32H7 based OpenPLC controller board

c. Digital Twin Application Development

The Digital Twin application was implemented based on the pre-designed interface. The 3D model of the mechanical system was incorporated into the application using Three.js, while real-time data communication was integrated using TCP/IP and WebSocket protocols (Figure 4).

d. System Integration

After all subsystems were completed, integration was carried out between the mechanical system, control system, and the Digital Twin application. Data communication was carried out using TCP/IP, MQTT, and WebSocket protocols. This integration ensures two-way interaction: sensor data is sent to the application, while commands from the application can move actuators in the physical system.

3. Results and Discussion

a. Results

The results of the prototype design and implementation demonstrate that the laboratory-scale Smart Factory system was successfully implemented according to the methodology. The mechanical system was created using a mini conveyor, linear axis, gripper, and pneumatic actuator, while the STM32H7-based control system with OpenPLC was able to read sensors and control the actuators stably.

The Digital Twin application, developed with Three.js and Node.js, successfully displayed system conditions in an interactive 3D visualization and supported bidirectional control.

Table 1. Digital Twin Smart Factory System Test Results

Components being tested	Success indicator	Result
Displacement sensor	Detect and count the workpieces	95% success rate
Conveyor actuators	Responsive according to logic	normal
Gripper and linear axis	Movement according to instruction	0.1mm accuracy
OpenPLC System Control	IO response time <500ms	200-300ms
Digital Twin Application	Realtime visualization	Realtime movement
Data communication	Bidirectional (monitor and control)	both
Sequence process	Sequenced according to process	normal

Initial testing showed that all components performed according to successful indicators, including sensors, actuators, controls, applications, and process sequences. Thus, this research demonstrates that the integration of Digital Twin and OpenPLC can support effective monitoring and control and provides a more flexible and economical alternative industrial automation solution.

b. Discussion

The development of the Digital Twin (DT) model integrated with an OpenPLC-based control system has proven effective in bridging the gap between physical and virtual factory environments. The bidirectional data exchange enabled real-time synchronization, allowing operators to monitor, analyze, and control industrial processes with high transparency. The use of OpenPLC as an open-source controller not only reduced system costs but also demonstrated sufficient reliability and flexibility for industrial applications. The integration of standard communication protocols such as Modbus TCP/IP ensured interoperability between the physical devices and the DT simulation platform, enabling continuous data flow and accurate virtual representation of the production process.

Furthermore, the proposed DT framework improved system diagnostics and maintenance efficiency by providing real-time visualization and performance analytics. The results indicate that virtual commissioning through the DT reduced setup time and minimized the risk of operational errors during testing and modification stages. However, scalability and latency remain key challenges when the system is expanded to handle more complex manufacturing operations. Future work should focus on integrating edge computing and machine learning algorithms to enhance data processing speed, predictive capabilities, and autonomous decision-making within the DT ecosystem.

4. Conclusion

This research successfully designed and developed a Digital Twin prototype in a laboratory-scale Smart Factory using an OpenPLC-based control system. The mechanical system, consisting of a processing station using a mini conveyor, linear axis, gripper, and pneumatic actuator, was successfully realized according to design. The STM32H7 microcontroller-based control system with the OpenPLC platform was able to read sensor input and control the actuator stably. Furthermore, the Three.js and Node.js-based Digital Twin application successfully displayed system conditions in real time in the form of interactive 3D visualizations and supported bidirectional control.

Test results showed that all system components performed according to the success indicators. The sensors were able to detect objects with a success rate of ..., the actuators responded well to commands, the control system had an average response time of ... . ms, and the Digital Twin application was able to perform monitoring and controlling functions stably. The process sequence also ran according to the programmed logic without any errors. Overall, this study proves that the integration of Digital Twin with an OpenPLC-based control system can increase the effectiveness of monitoring and controlling, provide flexible and economical automation solutions, and support the improvement of domestic products.

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