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Modeling and Simulation of a Digital Twin for SCADA-Based Industrial Pumping Systems

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***Abstract*— This paper presents the development and simulation of a digital twin model for an industrial cooling-water pumping system operated under a SCADA environment. The model was built in MATLAB/Simulink and includes pumps, pipelines, and valve behavior using real design data. Simulation results were compared with actual SCADA measurements, showing a difference of 6.6–10%, which confirms good agreement between the model and real system. The study shows how a digital twin can be used to analyze system performance, verify instrument accuracy, and improve control logic before implementation. It also outlines the steps for data collection, PLC–SCADA connection, and performance validation. The developed model provides a useful base for future predictive monitoring, design improvement, and real-time optimization in industrial automation.**

Keywords—SCADA System; MATLAB/Simulink; Industrial Pumping System; Hydraulic Modeling; System Validation; Process Simulation; Automation Engineering

I. Introduction

Digital Twin (DT) technology provides a virtual representation of physical assets, allowing real-time monitoring and optimization throughout an industrial system's life cycle [1]. Originating from Product Lifecycle Management (Grieves, 2002), its application has expanded rapidly with Industry 4.0 and IoT.

Digital Twin technologies have recently been applied to pumping and distribution networks to enhance operational awareness, decision-making, and performance optimization, demonstrating their growing relevance in water-sector applications [20], [21].

Pumping systems, essential for cooling and process water, can greatly benefit from DT integration by combining field data and physics-based simulation for predictive operation. In this study, a MATLAB/Simulink digital twin is developed for a cooling-water pump set controlled through a SCADA system. The model includes pump, valve, and pipeline dynamics, and is validated using field pressure data to demonstrate its accuracy and applicability.

II. Overview of Digital Twin Technology

A. Definition and Origin

A Digital Twin (DT) is, in general, a computer-generated virtual replica of a product, service, or process that is developed to monitor, analyze, and plan the performance of the entity over its life cycle. It was first introduced by M. Grieves in 2002 in relation to Product Lifecycle Management (PLM), highlighting the importance of integrating real-time data, simulation, and predictions throughout the life cycle of a system. [1]. In simple terms, the DT is an information system for dynamic and data-driven virtual representation of a physical system. As shown in Fig. 1, sensor data from the real pump system are continuously transferred to the virtual space, where they are processed and used to update the simulation model. The virtual subspaces (VS1–VS3) represent different analytical functions such as performance estimation or fault detection. The processed information is then fed back to support monitoring and decision-making, forming a closed loop between the physical and virtual systems.

B. Historical Evolution

- 1960s–1970s (Foundations): System dynamics (Forrester) introduced formal simulation of complex systems, while NASA paired physical hardware with numerical models during Apollo missions to anticipate and resolve faults [2], [3].

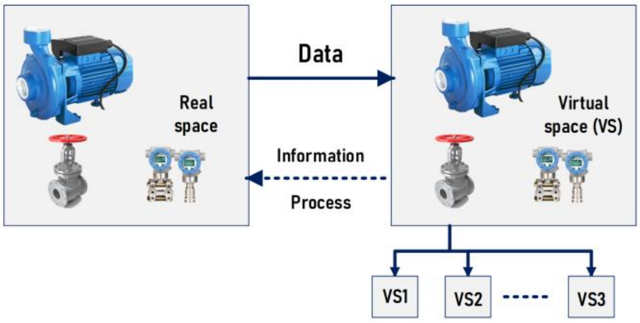

Fig. 1. Overview of the Real and Virtual Spaces in the Digital Twin Architecture

- 1980s (Early Computational): The rise of CAD and FEA enabled engineers to design digitally and test product geometries, marking the first widespread use of virtual modelling in engineering.
- 1990s (Data Integration): SCADA systems began linking real-time operational data with computational models, establishing feedback between plant performance and digital simulations.
- 2000s (First DT Concept): Michael Grieves formally described the "Digital Twin" in the context of Product Lifecycle Management (PLM), defining it as a computer-based representation of physical assets [4].
- 2010s (Expansion): NASA launched DT programs for spacecraft reliability [5], while Industry 4.0, IoT, and cloud platforms accelerated adoption. Commercial platforms like GE Predix emerged, and Gartner ranked digital twin among the top emerging technologies [5], [6], [7], [8], [9].
- NASA began Digital Twin implementation for spacecraft reliability [3]; Industry 4.0 ushered in CPS, IoT, and cloud-driven DTs [5]; GE Predix and city-scaling twins surfaced; Gartner included DT among top technologies, indicating expanding acceptance [6], [7], [8], [9]
- 2018+ (Platforms and standards): Healthcare adopted DTs during COVID-19, Siemens (Xcelerator) and NVIDIA (Omniverse) developed collaborative environments, and ISO/IEC initiated interoperability standards [10], [11], [12], [13].
- Future Directions (High-Level): DTs are converging with IoT and AI for predictive analytics, supporting smart cities, renewable energy, healthcare, and integration with VR/Metaverse technologies, with emphasis on open standards for cross-sector deployment [7], [11], [13], [14], [15], [16], [17].

C. Core Components and Architecture of Digital Twins

A Digital Twin links a physical system with its virtual model to monitor, predict, and improve performance. It combines five main parts: the physical system, data collection, virtual modeling, communication links, and application services. Sensors gather data from equipment, which are stored and processed for analysis. Communication protocols connect all layers to ensure continuous data flow.

In addition to those structural elements, DTs are also defined by three key concepts:

- Full life-cycle integration – covering design, operation, maintenance, and eventual decommissioning.
- Real-time or near real-time monitoring – enabling continuous supervision and interaction with assets.
- Bi-directional data flow – so that feedback from virtual models can influence and control the physical system.

A layered architectural view illustrating the interrelationship of these elements is presented in Fig. 2.

- **Physical Layer**: Collects real data from equipment and the environment through SCADA and IoT sensors [18].
- **Model/Virtual Layer**: Builds simulations to study and improve system behavior [18].
- **Information/Connection Layer**: Links databases and communication protocols such as IEC 61850, DNP3, and Modbus for data exchange [18].
- **Data Layer**: Stores and processes information to support analysis and decision-making [18].
- **Application/Program Layer**: Provides monitoring, optimization, and control using AI, SCADA/DCS functions, and cybersecurity tools [18], [19].

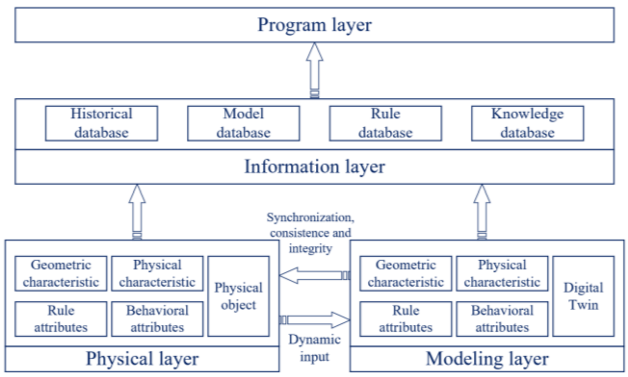

Fig. 2. The layered architecture of digital twin technology

D. Classification of Digital Twin Modelling

The definition and scope of a Digital Twin (DT) differ depending on purpose, modelling accuracy, and data availability. Broadly, DTs are classified into four categories:

1) Physics-Based Modelling - Uses mathematical and engineering principles.

- Static Twin: Captures geometry and material properties (e.g., TEG/TEC models).
- Dynamic Twin: Simulates real-time physical behavior under forces, motion, and environmental factors (e.g., CNC machine stability).

2) Data-Driven Modelling – Relies on real-time or historical data.

- Data-Replica Twin: Monitors and analyzes live data for forecasting and anomaly detection.

- Statistical Twin: Uses historical data to identify trends and predictive insights (e.g., industrial analytics).

3) Hybrid Modelling – Combines physics-based and data-driven methods.

- Integrated Twin: Merges physical laws with data analytics or ML for higher accuracy.
- Multi-Scale Twin: Links models at different levels (e.g., VSC converter control).

4) Domain-Specific Modelling – Tailored for industry needs.

- Product Twin: Models equipment and components.
- Process Twin: Represents generation, transmission, and distribution processes.
- System Twin: Optimizes entire networks such as energy systems.

III. SYSTEM BACKGROUND

A. System Configuration

A pump system for simulation is developed based on the operation of cooling water pumps. The pumps suction water from a 50 m³ storage tank and discharge it into the central industrial cooling system. The developed P&ID diagram is illustrated in Fig. 3.

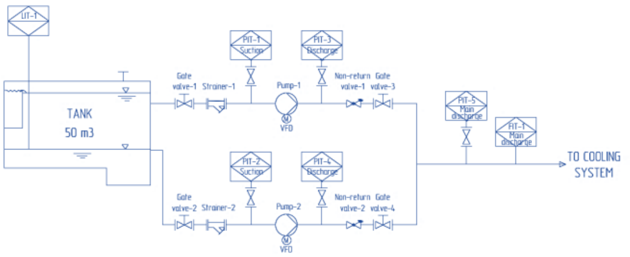

Fig. 3. The developed P&ID for the cooling-water pump system

The system includes two parallel pump lines, each with suction and discharge pipelines. Water passes through gate valves and strainers on the suction side to remove debris before reaching the pumps. Pressure indicators (PIT-1, PIT-2) monitor inlet conditions, while PIT-3 and PIT-4 record discharge pressures.

Both pumps are driven by Variable Frequency Drives (VFDs) and equipped with Local Control Panels (LCPs). Non-return valves prevent backflow, and gate valves allow isolation of each line. The discharge lines combine into a main header, where flow and pressure are measured by FIT-1 and PIT-5 before entering the cooling system.

Each pump delivers 400 m³/h at a total head of 105 m.

B. Instrumentation and Monitoring

The system uses several instruments for monitoring and protection. The tank level is measured by a Level Indicator Transmitter (LIT-1). Each pump is equipped with Resistance Temperature Detectors (RTDs) to monitor bearing and motor winding temperatures. Variable Frequency Drives (VFDs) control pump speed and provide feedback signals, including motor current, speed, and start readiness. Each pump also has a Local Control Panel (LCP) for manual operation, while remote operation and supervision are performed through the SCADA system.

A 3D model of the pump is presented in Fig. 4 for reference.

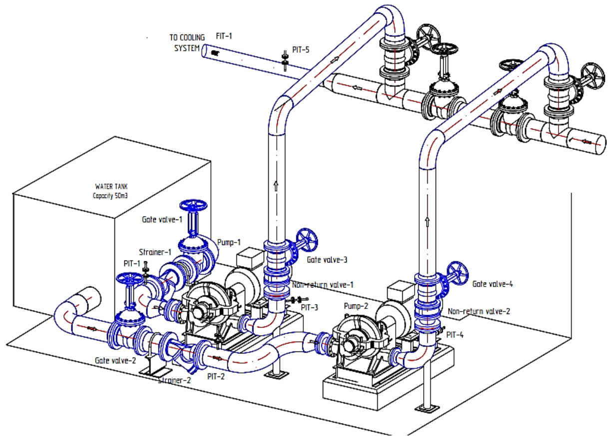

Fig. 4. 3D modelling of the pumps

C. SCADA I/O list

For the SCADA system, input and output signals for controlling and monitoring the pump system are summarized in Table I. These include start/stop commands, local/remote selections, operational feedback, analog measurements (current, pressure, flow, temperature), and RTD signals.

TABLE I. I/O list for system monitoring

Signal name	Equipment TAG	Signal of Equipment	Signal type
Start command	Pump-1 & Pump-2	LCP & VFD	DO
Stop command			DO
Local/remote selection			DI
Maintenance feedback			DI
Ready to start feedback			DI
Motor current feedback			AI
VFD speed feedback			AI
VFD speed command			AO
Bearing temperature DE	Pump-1 & Punp-2	Pump-1 & Punp-2	RTD
Bearing temperature NDE			RTD
Bearing temperature motor DE			RTD
Bearing temperature motor NDE			RTD
Winding temperature R			RTD
Winding temperature Y			RTD
Winding temperature B			RTD
Level indicator transmitter	LIT-1	LIT-1	AI
Suction pressure of pump-1	PIT-1	PIT-1	AI
Suction pressure of pump-2	PIT-2	PIT-2	AI
Discharge pressure of pump-1	PIT-3	PIT-3	AI
Discharge pressure of pump-2	PIT-4	PIT-4	AI
Main discharge pressure	PIT-5	PIT-5	AI
Main discharge flow	FIT-1	FIT-1	AI

D. Operation Philosophy

The cooling-water pump system operates automatically based on tank level, pump feedback, and protection interlocks. When the tank level is low (0.3 m), both pumps stop to prevent dry running; one pump runs in Auto mode above 0.5 m; and the second starts when higher flow or pressure is needed. Pumps start only if the level is sufficient, the VFD is ready, and no fault is active. The drive gradually increases speed until discharge pressure reaches about 8 bar.

Protection functions include level, temperature, and pressure trips, while non-return valves prevent backflow. Normally, one pump runs and the other remains on standby, with automatic alternation based on operating hours. Pumps can be controlled locally via the LCP or remotely through

SCADA. All alarms, trips, and system events are recorded and displayed on the SCADA interface for operator review.

IV. SCADA System Architecture and Components

A. PLC System Architecture Selection

The cooling-water pump system operates automatically based on tank level, pump feedback, and protection interlocks. Pump control is linked to level signals: when the level is low (0.3 m), both pumps stop to prevent dry running; one pump runs in Auto mode above 0.5 m; and the second pump starts when higher flow or pressure is required.

Each pump starts only when the tank level is sufficient, the VFD is ready, and no fault is active. The drive gradually increases speed until discharge pressure reaches about 8 bar. Stop commands are triggered manually or automatically when low level, high pressure, or emergency conditions occur.

Protection includes level, pressure, and temperature trips, while non-return valves prevent backflow. Normally, one pump operates and the other remains on standby, with automatic changeover based on running hours. Pumps can be controlled locally via LCP or remotely through SCADA, which also displays alarms and event logs.

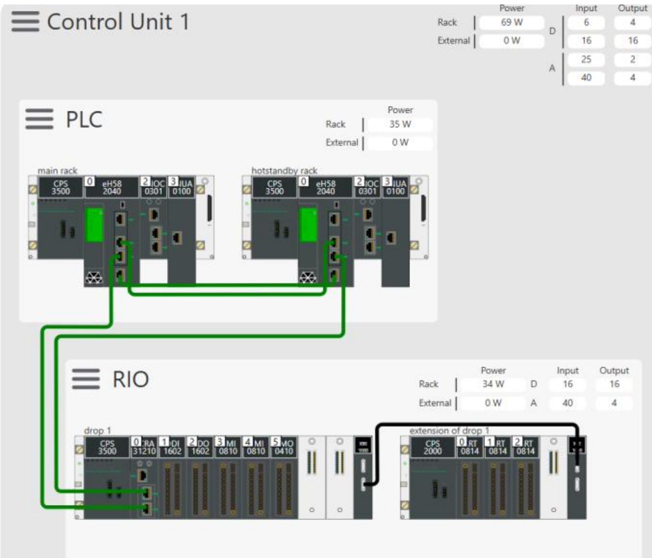

Fig. 5. PLC architecture

A redundant Ethernet ring connects the PLC racks and Remote I/O, ensuring reliable communication even if one link fails. At the network edge, an OPC UA/Modbus TCP server shares PLC data with both the SCADA system and MATLAB/Simulink, which serves as the digital twin platform. SCADA manages visualization, alarms, and data logging, while the digital twin uses live plant data for simulation and closed loop testing when permitted. This setup allows real-time monitoring and secure control of tank levels, pressures, flows, and pump operation.

The PLC reliability analysis (Section IV-B) is included because the digital twin depends on stable, deterministic data exchange with the control system. Ensuring CPU load, memory margins, and network performance remain within safe limits guarantees reliable synchronization between the physical system and the MATLAB/Simulink.

B. PLC System Reliability Simulation

The reliability of the PLC architecture was evaluated using simulation in Schneider's EcoStruxure. Results are presented in Figs. 7–9.

Fig. 6. Controller’s data and memory analysis

The selected BMEH582040C CPU showed very low memory usage—about 3% for both data and internal memory—leaving enough capacity for future expansion. The main task scan time averaged 8 ms with no overload, confirming that the controller runs smoothly and can handle additional logic or I/O without performance issues.

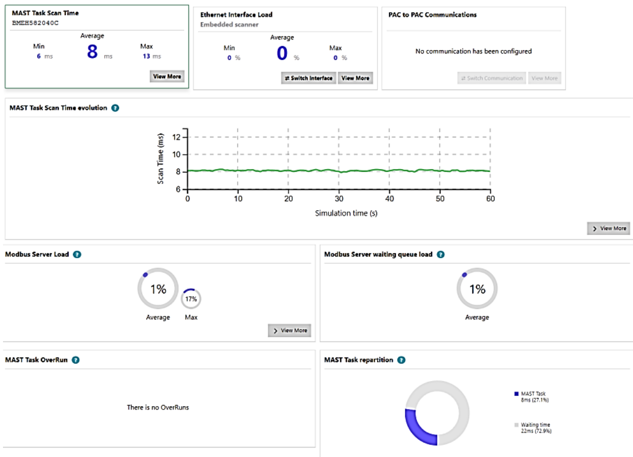

Fig. 7. Communication and Task Performance Monitoring

Ethernet interface usage stays below 1%, and no PAC-to-PAC communication is used. Cyclic tasks run steadily without delays or queue buildup, confirming that Modbus communication and task scheduling operate safely within stable performance limits.

C. SCADA system

The supervisory control and data acquisition (SCADA) system is built on top of the redundant PLC architecture to deliver process monitoring, visualization, historical logging, and operator control. The overall architecture is shown in Fig. 8.

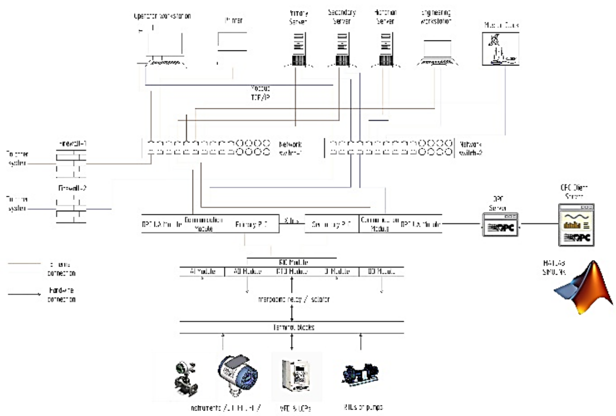

Fig. 8. The architecture of the SCADA system

The SCADA system includes operator and engineering stations, a historian for data storage, and two redundant servers for continuous operation. All components are linked through Ethernet switches and protected by dual firewalls to ensure network security. A master clock synchronizes all devices for accurate events and alarm timestamps.

The main and standby PLCs communicate with SCADA servers via Modbus TCP/IP, providing real-time process data to both operator screens and MATLAB/Simulink, which functions as the digital twin platform. This setup allows real-time co-simulation and safe testing of new control strategies without disturbing plant operation.

Field I/O modules connect directly to transmitters and sensors for level, pressure, flow, and temperature signals. Using signal isolators and relays ensures reliable and safe communication. Overall, the system offers stable data acquisition, fault-tolerant operation, and a strong foundation for predictive control and plant optimization.

V. Digital Twin Simulation Framework and Case Study

In the simulation, the suction side was modeled with DN300 piping and valves, while the discharge side used DN250 dimensions, as shown in Fig. 9. The suction tank was represented as an open reservoir to ensure flooded suction conditions.

The suction line (DN300, 3 m long) included gate valves and a variable strainer to simulate local losses. The pump was defined with a rated flow of 0.111 m³/s, head of 105.2 m, and speed of 1485 rpm, consistent with manufacturer data. Pump-2 was kept in standby with both valves closed.

On the discharge side, DN250 fittings were modeled with a non-return valve opening between 0.002–0.05 MPa and a 5 m discharge pipe. In the simulation, Pump-1 operated at 50 Hz with suction and discharge valves open, and pressure transmitters measured suction and discharge conditions

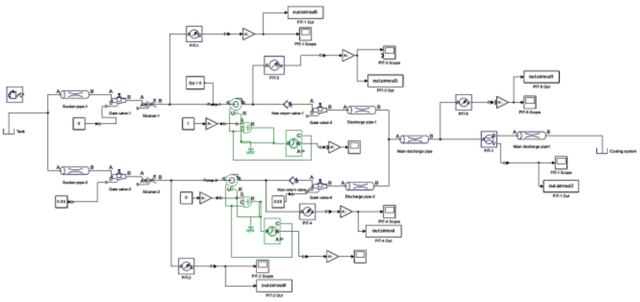

Fig. 9. Simplified digital twin model developed in MATLAB/Simulink.

Subsequent results for suction and discharge pressures are presented in Figs. 10 and 11.

Under real operating conditions, the measured discharge pressure was 9.5 bar, whereas the MATLAB model produced a value of 1.013e+01 (≈approximately 10.13 bar). This corresponds to an error of about 6.6%. On the suction side, the model predicted -1.170e+00 (≈−1.17 bar), whereas the field measurement indicated approximately −1.3 bar. The difference between the simulated and measured values can be explained by several practical factors.

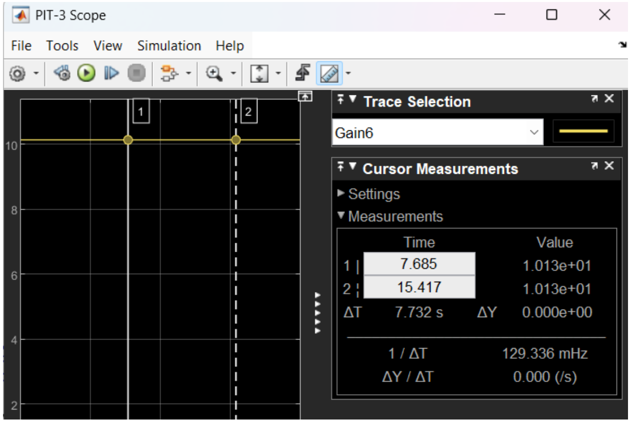

Fig. 10. Discharge side pressure (PIT-3) value in MATLAB/Simulink.

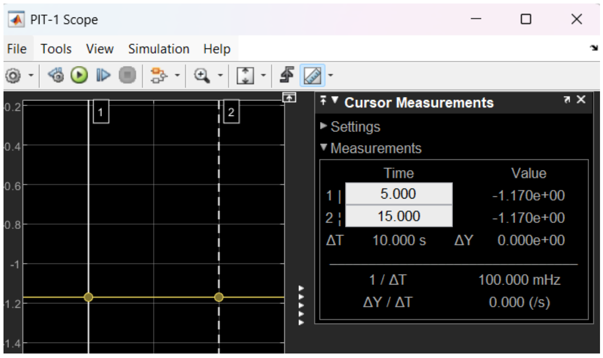

Fig. 11. Suction side pressure (PIT-1) value in MATLAB/Simulink.

In the model, some local losses—such as elbows, reducers, and valve behavior—were simplified, and the pump curve was used without considering efficiency changes at different operating points. In addition, the field sensors may have minor calibration deviations, and the simulation did not include transient effects that occur during pump speed ramp-up. These factors collectively contribute to the 6–10% discrepancy observed between the MATLAB results and the real measurements.

VI. Conclusion

A digital twin model of the pump system was developed in MATLAB/Simulink using DN300 and DN250 pipes for the suction and discharge sides. The model predicted a discharge pressure of 10.13 bar and a suction pressure of –1.17 bar, which closely matched the measured values of 9.5 bar and –1.3 bar. These small differences confirm that the model accurately reflects real system behavior within practical limits of valve and piping assumptions.

The study shows that a digital twin can effectively predict performance, detect design issues, and support equipment selection. Future work will include modeling pipeline bends, integrating VFD dynamics, and testing pump control strategies to enhance predictive maintenance, scenario analysis, and overall system optimization.

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