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Cyber-Physical System Architecture for Real-Time Warehouse Operations

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Abstract—Cyber-Physical Systems (CPS) combine computational and physical processes to enable real-time monitoring, control, and decision-making in industrial environments. This paper presents a CPS architecture designed for real-time warehouse operations within the *Intelligent Cyber-Physical Systems* (I-CPS) laboratory testbed at Polytechnique Montreal, Quebec, Canada. The proposed CPS architecture follows the IEC 62264 standard and integrates standards-based industrial protocols to enable communication between components, including Programmable Logic Controller (PLC), Decision Theater for real-time interactive decision making, Autonomous Mobile Robots (AMR), Desktop Computer Numerical Control (CNC) machine, Radio-Frequency Identification (RFID), proximity sensors, Quick-Response (QR) code reader, and camera vision system. Real-time data acquisition demonstrated a processing rate of 25 cycles per second,0.04 seconds per batch, supporting synchronization with a Digital Twin for operational monitoring. The proposed CPS architecture lays the foundation for addressing challenges in anomaly detection by introducing anomaly injection techniques as a future direction to mitigate the lack of naturally occurring anomalies. It contributes to the evolution of CPS architecture tailored for Industry 4.0 applications.

Cyber-physical system; communication protocols; IEC 62264 standard; data collection; digital twins; anomaly detection

I. INTRODUCTION

Industry 4.0 represents the transformation of industrial processes through digitalization and interconnected systems. At the core of this transformation is the Cyber-Physical Systems (CPS), which integrate sensors, data flow, communication network, and physical components to enable real-time monitoring, decision making and control [1]. These systems use the Internet of Things (IoT) to facilitate communication between sensors, machines, control systems and automation in industrial environments [2]. CPS play a role in achieving the objectives of Industry 4.0 by providing data-driven insights for optimizing production and manufacturing operations.

Despite their benefits, the deployment of CPS presents challenges, including interoperability among heterogeneous systems, and the need for real-time data processing [3]. Addressing these challenges is needed to leverage CPS capabilities for intelligent decision-making and resource allocation in industrial settings. The concept of CPS has been studied in literature, with various definitions emphasizing different aspects of its integration into industrial applications. One perspective defines CPS as a system combining computation, communication, and control to create intelligent industrial environments [4]. Another view describes CPS as a framework that integrates computational and physical processes through embedded sensors, actuators, and networked controllers, ensuring real-time adaptability [5]. These systems often incorporate Digital Twins to enhance real-time feedback mechanisms and process optimization, where Digital Twins are virtual representations of physical systems synchronized with real-time data to support decision-making [6].

Several CPS architectures have been proposed in the literature to address various manufacturing challenges. One system [7] supports cloud manufacturing integration by leveraging a suite of communication protocols. Another system [8] focuses on Cyber-Physical Production Systems (CPPS) and incorporates several industrial communication protocols while adhering to the IEC 61131-3 standard for programmable controllers, promoting standardized automation and robust industrial process control. A third system [9] targets shop floor manufacturing, employing a range of communication protocols but does not specify adherence to any recognized standards, potentially limiting its applicability in global manufacturing settings.

Although CPS has been studied across various domains, most research primarily focuses on production and manufacturing applications. However, the architectural implementations of CPS in warehouse environments remain underexplored. Existing research often limits itself to the use of Radio-frequency identification (RFID) technology for material tracking without addressing the integration of advanced CPS architecture [10]. This gap highlights the need for further investigation into CPS architecture tailored for warehouse management, including aspects such as real-time synchronization, anomaly detection, and intelligent resource allocation.

Real-time data collection and Digital Twin integration play a role in enabling CPS operations. Digital Twins create synchronized virtual models of physical assets, improving decision-making by simulating real-time operational conditions [10]. However, existing architectures do not fully address the integration of real-time data pipelines with Digital Twin communication, resulting in gaps in synchronization and system responsiveness [7]. Research suggests that overcoming these challenges requires a data exchange framework that supports continuous interaction between cyber and physical components [8].

Anomaly detection in CPS is important for warehouse environments to identify faults early. Research has explored various detection mechanisms, but few studies have examined synthetic anomaly injections to improve detection accuracy [9]. Detection models depend on real-world data, which may not cover all failure scenarios. Synthetic anomaly injections, meaning artificially created or simulated anomalies rather than naturally occurring ones, can improve detection frameworks by introducing controlled fault cases for training and validation [11]. Some dynamic models exist, but they often do not include artificial anomaly generation, limiting their accuracy [10].

In summary, existing research on CPS highlights a lack of detailed CPS architectures tailored for real-time data collection. This paper addresses this gap by proposing a CPS architecture that integrates real-time data acquisition and communication within a warehouse testbed, following the IEC 62264 standard [12]. This architecture serves as a foundation for the implementation of Digital Twin in the laboratory, supporting future developments in data synchronization, anomaly detection, and decision-making applications.

The rest of this paper is organized as follows: Section 2 presents the proposed CPS testbed architecture for real-time warehouse operations. Section 3 explains how real-time data is collected and managed in the proposed testbed. A summary and future work is provided in Section 4.

II. METHODOLOGY

This study presents a CPS architecture for real-time warehouse operations. The methodology follows a structured approach, to ensure the architecture's practical functionality and adherence to industrial standards. To develop the Digital Twin of the warehouse system, specific hardware and software components were selected. A Programmable Logic Controller (PLC) served as the central component, coordinating various devices and facilitating system-wide communication. The proposed CPS was designed to align with the IEC 62264 (Enterprise-Control System Integration) industrial automation pyramid hierarchy [12]. Standard-based industrial communication protocols were configured to enable connectivity between cyber and physical components. A structured data acquisition pipeline was implemented for real-time data collection. Python scripts were used to interface with the PLC and retrieve sensor data.

III. THE PROPOSED CYBER-PHYSICAL SYSTEM ARCHITECTURE

This section presents the proposed CPS architecture and key components of the *Intelligent Cyber-Physical Systems* (I-CPS) laboratory testbed at Polytechnique Montreal, Quebec, Canada. It details the interconnected hardware and software elements that form the basis for research and development within the laboratory's smart warehouse operations focus.

A. The I-CPS testbed at Polytechnique Montreal

The I-CPS laboratory at Polytechnique Montreal (Fig. 1) is a cutting-edge testbed for innovative research in collaboration with industrial partners to develop a smart and connected warehouse. Designed as a modular testbed, the laboratory allows components to be upgraded, replaced, or reconfigured independently. The I-CPS laboratory is envisioned as a testbed for research and industrial collaboration in Industry 4.0, providing a platform to develop an adaptive CPS. Here, "adaptive" refers to systems that can dynamically respond to changes in operational conditions, using real-time data and algorithms to modify their behavior or workflows as required. The I-CPS laboratory facilitates the development and validation of solutions related to intelligent decision support via digital twin technology, real-time and data-based maintenance for physical asset health management, human-machine interaction (HMI), intelligent robotics, user experience, cybersecurity, and enabling communication network technologies.

Fig. 1a and 1b illustrate the I-CPS laboratory setup at Polytechnique Montreal, which comprises three Automated Mobile Robots (AMR); two transporters and one dual-arm manipulator navigating between various workstations. These workstations facilitate: (1) product manufacturing using a Desktop Computer Numerical Control (CNC) machine; (2) quality inspection via a camera vision system; (3) AMR and product tagging with a Radio-Frequency Identification (RFID) writer; (4) AMR and product tracking with an RFID reader; and (5) product identification via a QR code reader. The testbed also incorporates designated waiting areas, including: (1) unloaded waiting area for transporter AMR; (2) a product pick-up area; (3) receiving storage area for incoming products; (4) shipping storage area for outgoing products; and (5) a quarantine area for non-conforming products. The I-CPS laboratory also features a Decision Theater, intended to provide dashboards and real-time monitoring of key performance indicators, system status, and operational data, thereby supporting informed decision-making and efficient warehouse operations.

B. The Hierarchy of the proposed CPS architecture

The proposed CPS architecture aligns with the industrial automation pyramid of IEC 62264 (Enterprise-Control System Integration) [12] hierarchy shown in Fig. 1c.

This work presents small-scale, laboratory-based CPS architecture. It implements levels 0, 1 and 2 of the IEC 62264 standards, covering the physical process, sensing/actuation, and supervisory control with real-time monitoring. We did not address levels 3 and 4, which deal with enterprise management and strategic decisions, as these require larger-scale systems and IT infrastructure.

1) Physical Process (Level 0):

The warehouse process begins with stocking incoming products manufactured by the Desktop CNC machine, which serves as the supplier. These products are stored in the receiving storage area before progressing through various stages, as illustrated in Fig. 1c. When a customer's order is received, the transporter and manipulator AMR move the outgoing products to the shipping storage area. During this process, products pass through tracking, inspection and identification workstations, including RFID, camera vision system, and QR code scanning to ensure traceability and quality control. Based on inspection results, conforming products proceed to the shipping zone, while non-conforming items are directed to the quarantine zone for further evaluation. They are either reworked or scrapped.

2) Sensing and actuation (Level 1):

This level focuses on data collection and device actuation based on sensor inputs, forming the foundation for higher-level decision-making. Key features include sensing environmental variables (e.g., inventory levels) and actuating robots tracking material through the Programmable Logic Controller (PLC) for real-time operational responses.

3) Supervisory control/real-time monitoring (Level 2):

This level represents the centralized architecture of the testbed's supervisory processes, which are managed through the industrial PLC and software based on the software TIA Portal. The PLC acts as the central processor, coordinating various devices and ensuring communication across the system. The Siemens Edge PC serves as a dedicated computer for managing the AMR, providing additional computational resources to handle robot-specific tasks and ensuring the execution of the operation within the warehouse environment.

Table 1 summarizes the I-CPS warehouse components, their role in warehouse operations and their corresponding IEC 62264 levels. Components at Level 1 focus on data collection and execution, while Level 2 components facilitate supervisory control and coordination. Networking and communication devices are classified separately, as they do not correspond to a specific IEC 62264 level.

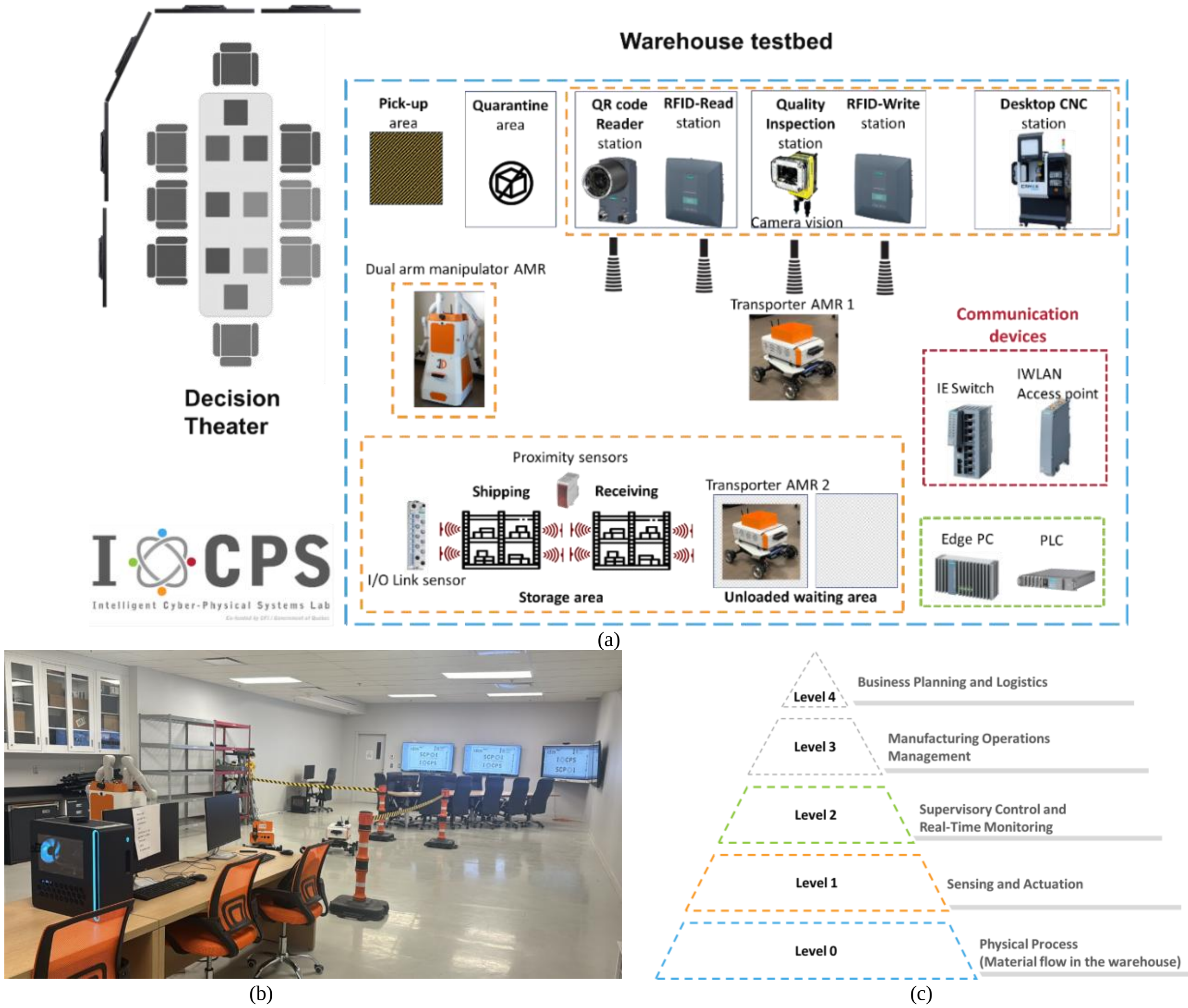
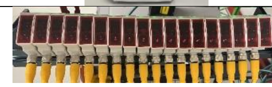
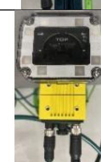


Figure 1. (a) Setup of the I-CPS testbed with IEC 62264 levels; (b) I-CPS Laboratory at Polytechnique Montreal (Quebec, Canada); (c) Industrial automation pyramid for the proposed CPS, adapted from IEC 62264 [12]

TABLE I. INDUSTRIAL AUTOMATION COMPONENTS AND THEIR IEC 62264 LEVELS

<table>
<tr><th>Component</th><th>Description</th><th>IEC 62264 Level</th><th>Image</th></tr>
<tr><td>Transporter AMR</td><td>The transporter AMR navigates the warehouse autonomously, performing material handling tasks. It transports products between different stations:
moves the product to the RFID write/read station to write/read the ID from the tag on the AMR.
moves the product to the quality inspection station (camera vision system)
moves the product to QR code read station to get the product’s engraved code.</td><td>Level 1</td><td></td></tr>
<tr><td>Dual Arm Manipulator AMR</td><td>The dual arm manipulator AMR picks and places products in the warehouse.
picks the product from the CNC Desktop machine,
stores products on the storage shelves
loads the product on the transporter AMR.
The arm moves and rotates products during the product’s inspection, loading and storage process.</td><td>Level 1</td><td></td></tr>
<tr><td>Proximity Sensors</td><td>Diffuse infrared (IR) proximity sensors attached to the receiving and shipping shelve racks are used to detect if a storage cell is free or occupied.</td><td>Level 1</td><td></td></tr>
<tr><td>RFID</td><td>RFID Read/Write is an industrial module that can facilitate real-time robot and product tracking using RFID-tagged items.</td><td>Level 1</td><td></td></tr>
<tr><td>QR Code Reader</td><td>The QR code reader reads the product’s QR code to identify the product and associate it with the AMR.</td><td>Level 1</td><td></td></tr>
<tr><td>Camera Vision System</td><td>Used for quality control and precise item identification, these cameras ensure defect operations.</td><td>Level 1</td><td></td></tr>
<tr><td>I/O Link modules</td><td>I/O link modules periodically read the diffuse IR proximity sensors voltage and send the information to the industrial controller.</td><td>Level 1</td><td></td></tr>
<tr><td>Desktop CNC machine</td><td>The Desktop CNC machine is a compact, computer-controlled device that performs machining operations based on programmed instructions. Its role is to manufacture products needed for warehouse operations or inventory.</td><td>Level 1</td><td></td></tr>
<tr><td>PLC</td><td>The PLC hosts the controller’s software that aggregates the warehouse state and sends control commands to all warehouse equipment when needed.</td><td>Level 2</td><td></td></tr>
<tr><td>Edge PC</td><td>The Edge PC serves as a bridge between the PLC and the AMR (translator between Robot Operating System 2 (ROS2) and Message Queuing Telemetry Transport (MQTT) communication protocols).</td><td>Level 2</td><td></td></tr>
<tr><td>Industrial Ethernet (IE) Switch</td><td>Manage network communication between industrial devices.</td><td rowspan="2">Not applicable</td><td rowspan="2"></td></tr>
<tr><td>Industrial Wireless Local Area Network (IWLAN) access points</td><td>The PLC is connected to an IWLAN access point using an IE switch. The IWLAN access point enables wireless communication for industrial devices.</td></tr>
</table>

C. Multi-Layered Control Architercture

Within the proposed CPS architecture, software integrates and coordinates the testbed's hardware components.

The system utilizes standards-based industrial communication protocols, including Robot Operating System 2 (ROS2), Process Field Network (PROFINET), and Message Queuing Telemetry Transport (MQTT), to enable real-time monitoring and data exchange.

Fig. 2 illustrates the interaction between hardware, software, and communication protocols in the proposed CPS architecture for real-time warehouse operations. The mutli-layered control architecture consists of four layers: the application layer, where the Digital Twin orchestrates sequence logic and decision-making; the control and data Layer, which includes an Edge PC and PLC for processing and control; the communication layer, integrating ROS2, MQTT, and PROFINET to facilitate data exchange between system components; and the devices layer, comprising transporter and Manipulator (AMR) and industrial devices such as RFID modules, sensors, vision camera system, I/O Link modules and Desktop CNC machine. This structure enables real-time monitoring, synchronization, and automation within an Industry 4.0 environment.

Each industrial automation device (I/O Link modules, QR code reader, RFID, and camera vision system) was configured for IP networking and communication with the PLC over PROFINET. ROS2 and MQTT handle message-based communication between the transporters AMR and the manipulator AMR. All this configuration is done using a combination of the individual web interfaces built into the devices and a custom project using TIA Portal.

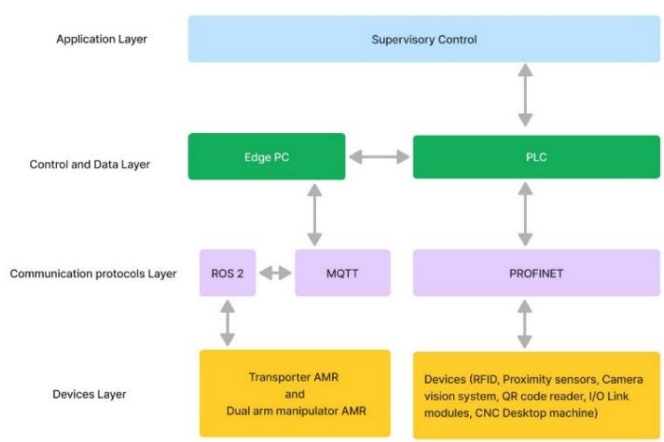


Figure 2. Multi-Layered Control Architecture for the Warehouse Testbed

IV. Data Flow: Linking Physical Systems to the Virtual System

An architecture for CPS implementation was proposed in Section II, integrating hardware and software components. The interaction between these components follows a structured data flow, where information moves through different layers. This section describes the data flow within the system, detailing how data is collected and transmitted.

Real-time data collection is needed for integrating the physical system's information into the system architecture, enabling continuous monitoring, control, and data-driven decision-making. The proposed testbed employs a structured data acquisition process that ensures interaction between physical systems and Digital Twin. As illustrated in Fig. 3, the system facilitates bidirectional communication between the software TIA Portal (PLC) and Python/Snap7, supporting real-time synchronization and structured data management.

Sensors continuously send data to the PLC, which updates the available data in TIA Portal. Python uses the Snap7 library to connect to the PLC and to retrieve a snapshot of all available data through PUT/GET requests. The acquired data is then processed and stored in Excel file for analysis, reporting, and further applications such as Digital Twin integration and anomaly detection. Once the data exchange is completed, the connection to the PLC is disconnected.

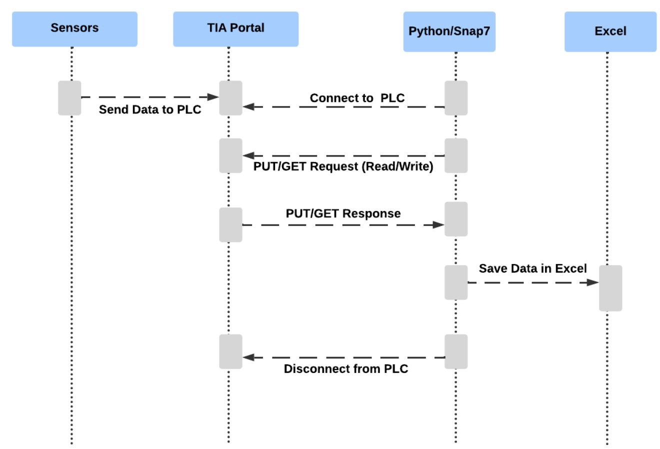


Figure 3. UML Sequence Diagram: Data Flow Between Physical Systems and Digital Twin

While the full system architecture includes numerous hardware components, the implementation presented in this section focuses on capturing snapshot readings from two devices: proximity sensors and RFID devices. The implemented system captures these readings, along with data from TIA Portal, processing them at a rate of 25 batches per second (0.04 seconds per batch). Each batch represents a complete snapshot of device states at that instant, enabling continuous monitoring. This data collection facilitates real-time synchronization with the Digital Twin, updating the excel sheet and database with each batch.

V. Conclusion

This paper presented CPS architecture for warehouse management, while emphasizing real-time data collection and paving the way for Digital Twin synchronization and anomaly detection. By integrating standard-based industrial protocols such as ROS2, PROFINET and MQTT, the proposed architecture enables communication among the system's components, including AMR, Desktop CNC machine, proximity sensors, QR code reader, RFID and vision camera system.

The proposed CPS demonstrated real-time data acquisition capabilities from two devices (proximity sensors and RFID) by achieving a processing rate of 25 cycles per second (0.04 seconds per batch), and by supporting synchronization with the Digital Twin.

One of the challenges was the lack of naturally occurring anomalies in the collected data highlighting the need for techniques to improve anomaly detection. Future work will focus on implementing anomaly injection methods to enrich training datasets and enhance detection accuracy, ensuring better integration with the Digital Twin. Additionally, optimizing the data pipeline to improve real-time synchronization with the Digital Twin remains an area of ongoing development.

This work represents a step forward in advancing CPS architecture for Industry 4.0 applications, bridging the gap between theoretical research and practical implementation. By addressing current challenges and continuing to innovate, this framework has the potential to serve as a foundation for scalable, adaptive, and intelligent CPS solutions in smart warehousing.

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