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Integrating an AS/RS with Digital Twin in a Physical Internet network

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Abstract: The Physical Internet (PI) is an innovative approach to goods distribution, inspired by the principles of the Internet, with an emphasis on information sharing and collaboration. Within a PI network, logistics operators contribute by providing π-nodes that perform various functions such as receiving, transporting, storing, and redistributing π-containers, which are the unit loads used in PI. The Digital Twin (DT) technique involves the creation of a digital model that replicates the functioning of real-world systems. This paper seeks to demonstrate the potential benefits of implementing a DT of a π-node within an entire PI network. Specifically, it examines the case of a π-store, a unique type of node tasked with receiving goods, temporarily storing them, and subsequently releasing them. In this study, the successful development of an automated storage and retrieval system DT is presented, as well as the various PI interface models aimed at analyzing the types of information that could prove valuable when sent to or received from the network. Finally, the ways in which information received from the PI can improve the effectiveness of the node DT and, in turn, the efficiency of the warehouse system are examined.

Keywords: Physical Internet, Digital Twin, Automated Storage and Retrieval System, Supply Chain Management

I. INTRODUCTION

The PI (Physical Internet) is an innovative approach to goods distribution that adopts principles from the Internet. Key components of the PI include π-nodes and π-containers, which facilitate efficient movement and storage of goods. π-nodes perform diverse functions within the network, while π-containers provide standardized and interoperable packaging (Montreuil, 2011). The PI is currently in an embryonic stage due to the incomplete maturity of the theoretical models that describe it and the complexity of its practical implementation. In fact, numerous changes are required in the way logistics is conceptualized, as well as the economic models that govern logistics processes. However, it represents an important horizon for aligning global logistics with global climate plans for reducing CO2 emissions (Pan et al., 2017).

In recent years, Automated Storage and Retrieval Systems (AS/RS) have become a widely used technology to support logistics and supply chain operations. These systems are capable of storing items in specific locations and retrieving objects without the need for human operators (Ferrari et al., 2022). AS/RS systems consist of storage racks, storage and retrieval machines, Input/Output (I/O) points, and conveyors (Lerher et al., 2010). They offer several advantages over traditional warehousing systems, including high space utilization, reduced labor costs, short retrieval times, and improved inventory control (Boysen & Stephan, 2016).

A Digital Twin (DT) is a simulation-based virtual counterpart of a physical system that utilizes real-time data synchronization to optimize the actions of the physical system (Kritzinger et al., 2018). DTs have been applied in various industrial contexts, such as predicting aircraft damages (Tuegel et al., 2011) and aiding cyber-physical production systems (Ding et al., 2019). The concepts of the PI and the DT of an AS/RS are deeply intertwined (Siprés et al., 2023; Rizopoulos et al., 2023; Vijay et al., 2023). The PI can model an AS/RS as a π-store, which is a specific π-node responsible for receiving, storing, and releasing packages at predetermined times. The need for a routing strategy for π-containers that makes the PI a participatory and efficient network necessitates some form of forecasting of the network behavior over time. At the same time, the network must have the ability to re-optimize itself as conditions change or new π-containers arrive. A DT, even at the node level, can help fulfill these two requirements.

Therefore, this paper aims to analyze how a real system can be connected within the PI, focusing on specific protocol layers identified in the literature and examining the benefits for both the PI network and the physical system itself. A valid approach is proposed for various types of π-nodes, specifically derived from the needs identified through the analysis of a specific case, namely the DT of an AS/RS in a research laboratory. The remainder of this article is structured as follows. First, a literature review focused on PI protocols is proposed. Then, the model to integrate the concepts of PI, DT and AS/RS is presented, followed by the description of a case study. Finally, discussions and conclusions are outlined.

II. LITERATURE REVIEW

The PI relies on protocols to enable effective communication and coordination among nodes, ensuring real-time information exchange (Montreuil, 2011; Sternberg & Denizel, 2021).

While the PI is still in its early stages (Pan et al., 2017), it is evident that protocols play a crucial role in orchestrating a PI network (Pothen et al., 2023). However, a universally recognized adopted standard for these protocols is yet to be established.

A hierarchical division of PI protocols has been proposed. Lower-level protocols (LPs) ensure the physical integrity of π-containers and other physical components in the PI. They govern the transfer of π-containers from one π-node to another. Higher-level protocols (HPs) focus on the integrity and performance of the PI networks, routing π-containers through these networks, and managing shipments and distributions of π-containers (Colin et al., 2016; Gontara et al., 2019; Montreuil, 2011; Sun et al., 2018). As an example of such HPs, shortest-path algorithms are employed to determine the path of π-containers in a PI network to optimise operational costs (Sarraj et al., 2014).

Furthermore, when each π-container is equipped with unique identity and a smart tag (Tran-Dang et al., 2020), it is possible for an HP to facilitate information exchange trough the network and make informed decisions such as allocating π-containers to suitable clients and transportation service providers alike. HPs can also determine optimal storage locations and retrieval time for the π-containers. Moreover, HPs can coordinate transportation vehicles to perform en-route disassembly and reconsolidation of π-containers at multiple π-nodes, consolidating fragmented product flows before delivering them to their final destinations (Peng et al., 2021; Sohrabi et al., n.d.). The coordination can be carried out both ex-ante and in real-time, potentially even reaching the point of redirecting trucks on the fly if it proves advantageous (Peng et al., 2021).

Regarding the intervention of HPs in defining the economic sustainability of the network, two main models can be identified (Peng et al., 2021c; Tran-Dang & Kim, 2021). The first can be defined as "collaborative", where the HPs are responsible for the distribution of revenues among the stakeholders of the network (Chargui et al., 2019; Sohrabi et al., n.d.). The second one can be defined as "competitive", where the participation of a π-node in a transport process is subject to a pre-agreed amount, such as through an auction system (Briand et al., 2022).In summary, while the PI holds great promise as a technology, its practical implementations are still limited at present. Moreover, as emerged from the literature review, there is a lack of a comprehensive model that combines PI and DT concepts to enhance the efficiency and effectiveness of AS/RS operations. Additionally, there is a need for a model that integrates HPs in this context. Therefore, the primary objective of this research article is to address this significant research gap by proposing a novel conceptual model that integrates PI and DT for AS/RS. Furthermore, a practical case study is presented to demonstrate the feasibility and potential benefits of the proposed model.

III. METHODOLOGY

A. *Overview*

As no definitive system or dominant trend emerges from the literature regarding how higher protocols should interact with nodes, the aim of this research is to propose an approach that is as general as possible.

To achieve this, the concept of perturbations is introduced. Assuming the node in question is at rest or following its predetermined programming, any request to do things differently, immediately or in the future, is considered a perturbation. For example, if an automated warehouse was scheduled to move three boxes tomorrow and is asked to move a fourth, this is a perturbation. Similarly, if it was scheduled to move four boxes, but one movement is cancelled, this is also considered a perturbation. Perturbations serve as the mechanism by which HPs command nodes, forcing them to modify their programming to ensure the dispatch of π-containers.

This research aims to develop a digital replica of the physical system, i.e. a DT, capable of predicting system evolutions in fractions of a second.

The impact of perturbations on the physical machine varies depending on the adopted model. In a collaborative model, the physical machinery directly responds to perturbations proposed by the higher protocols of the network. Conversely, in a competitive model, these perturbations are mediated by a logical-economic layer controlled by the node owner, which manages economic aspects. The DT here proposed aims to be agnostic.

B. *Exchanged information and benefits*

Implementing the DT, in response to a perturbation request, a node could provide estimates for managing the perturbed π-containers, forecast increased consumption in terms of overhead (electricity, maintenance staff overtime, machine wear), as well as recalculate estimates for the currently managed π-containers.

To better illustrate this concept, let's consider a practical example. The network proposes to perturb the node's actions by introducing a new π-container to be managed, which needs to be retrieved at time 1 and delivered at time 100. The DT analyses the current forecast, which includes all the ongoing and future operations that the machine is expected to perform, and an internal optimizer re-optimizes these operations in response to the perturbation proposal. The DT then provides a new forecast that incorporates the perturbation proposal. From this forecast, it is possible to determine, for instance, a delivery precision measure representing the likelihood of the π-container being delivered on time at time 100. If it is 95%, it means that only in those cases the π-container would be delivered punctually, and there is a 5% chance of delay. Additionally, the DT can provide updated estimates for all other managed π-containers, such as indicating that to achieve a 95% delivery precision for that specific package, the precision of another package needs to be reduced by an additional 10%. At the same time, the DT can calculate that it is also possible to increase the delivery precision of that particular π-container and the others being managed, at the cost of consuming more electricity.

Figure 1 represent an outline illustrating an example of information exchange framework in both the collaborative and competitive models.

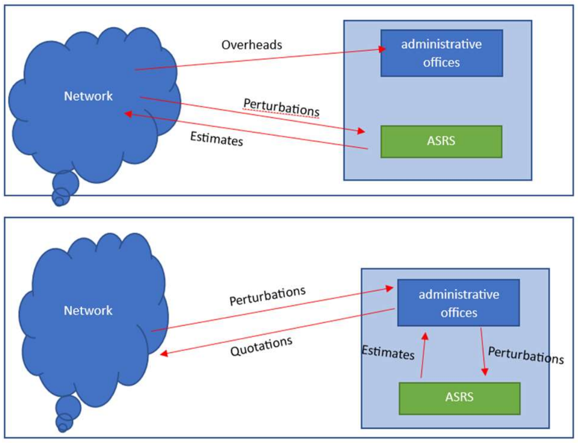

Fig. 1. Summary of a potential information exchange scheme with the collaborative model (top) and competitive model (bottom).

However, the DT proposed would enable the higher protocols of the PI to work with a sort of switches, which determine whether to increase precision in managing one π-container or another, or to save electricity, in order to optimize the network's functionality (collaborative model) or the node's profit (competitive model). Since the DT concept proposed here is agnostic to the model adopted, benefits of integrating PI and DT can be identified in both competitive and collaborative networks. A schematic overview of the benefits is summarized in Table 1.

IV. CASE STUDY

A. The Maxi-Shuttle System

The integration of the concepts of PI, and DT is studied through a case study focusing on an automated warehouse installed in the laboratories of Politecnico di Torino. The most common AS/RS configuration consists of an automated Handling Machine (HM) operating in an aisle with both horizontal and vertical movements. The Multi-Level Shuttle (MLS) system is a specific application of this stacker crane configuration, designed to be installed in logistics systems that require high performance. The MLS is also suitable for installation in reduced spaces due to its small size and weight (Figure 2).

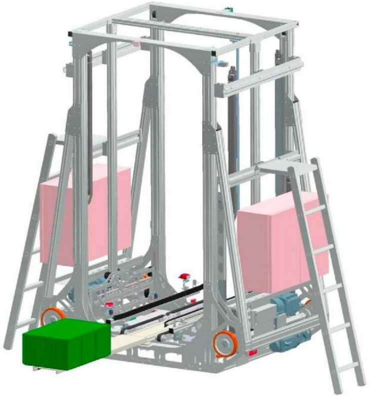

Fig. 2. The Multi-Level Shuttle system

From a design perspective, the MLS can move small ULs, such as plastic totes or trays, along three axes. The MLS is generally aisle-captive, which means that the HM works permanently in one aisle of the storage rack. The rack has a double front, with storage locations designed to accommodate multiple ULs. The MLS is also

TABLE I
BENEFITS OF A DT OF A PI-STORE WITHIN THE PI

	Collaborative	**Competitive**
For a π-store with DT	More accurate estimates on the future state of the AS/RS. Better decision-making in the present and resulting. Reduced overhead costs (e.g., energy, staff overtime)	The possibility of utilizing one's own DT to make estimates with fully automated protocols, thus leveraging the sophistication of the DT system to enhance profitability.
For PI network	The ability to obtain forecasts on the future state of the node and estimate the costs of a perturbation, thereby enabling improved routing of π-containers.	

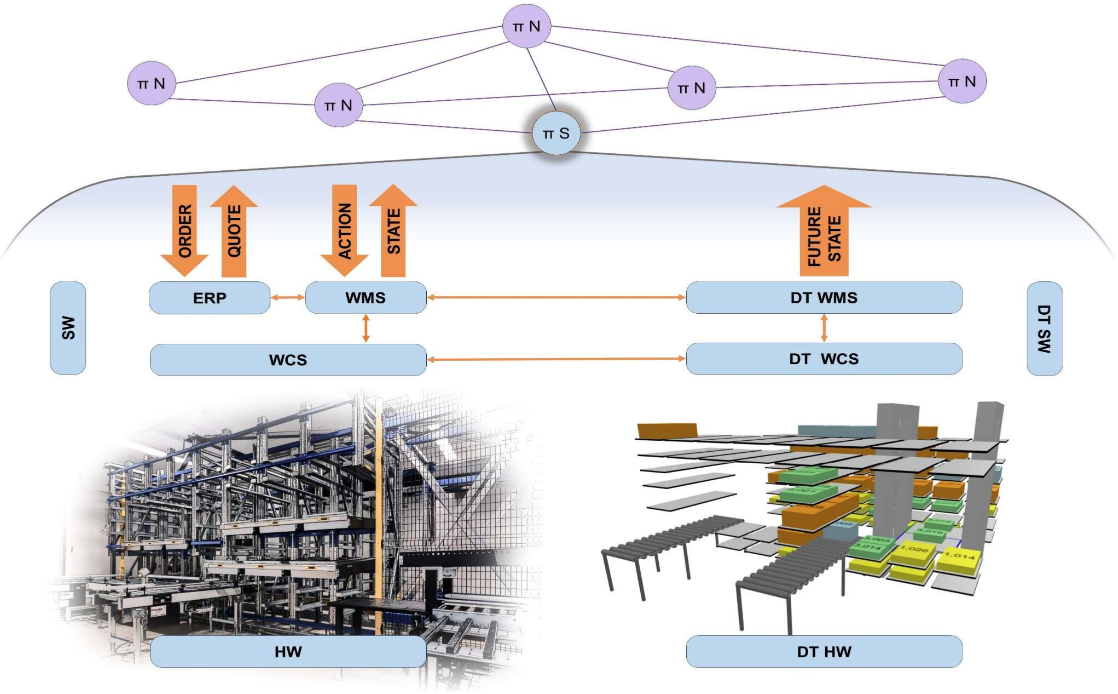

Fig. 3. Conceptual diagram of the DT and the information exchanged by each element of the DT and the physical system with the PI.

equipped with an input/output (I/O) roller conveyor system.

From an operational point of view, the MLS follows a priority based (PB) inventory policy, i.e. each storage location is characterized by a priority that determines the preference with which that storage location is selected for a storage operation. Moreover, the HM operates in either Single Command (SC), Dual Command (DC), or Multiple Command (MC) mode. In addition, if the UL to be retrieved is blocked by other ULs, the ULs stored in front of it are relocated based on a Nearest Neighbour (NN) policy, i.e., the closest available storage location.

B. *The PI DT*

The integration of a AS/RS with a DT within a PI network presents a promising approach for implementing efficient and intelligent logistics operations. This section proposes a framework for describing the integration of a warehouse DT within a node of the PI network, specifically focusing on the concept of a π-store (Figure 3). The π-store node serves as a dedicated facility for storing and retrieving π-containers, utilizing an automated storage and retrieval system of the MLS type. The framework emphasizes the interconnectivity between the real system and its virtual replica, enabling simulation-based analysis and prediction of the future state of the warehouse operations.

The real system within the π-store node is composed of both hardware (HW) and software (SW) components. The HW component includes all physical infrastructure of a MLS, such as racks, conveyors, and automated storage and retrieval equipment. The SW component comprises a Warehouse Management System (WMS), a Warehouse Control System (WCS), and a Enterprise Resource Planning (ERP) system.

The WMS serves as a central information system for managing and controlling various warehouse activities, including inventory management, order processing, and warehouse optimization. It provides real-time visibility into inventory levels, locations, and movements, facilitating efficient resource utilization and order fulfilment.

In parallel, the WCS acts as an intermediary between the WMS and the automated equipment, overseeing real-time activities within the warehouse. It ensures seamless coordination, translating orders and tasks received from the WMS into storage and retrieval missions for the MLS. The WCS optimizes material flow, monitors equipment status, and manages task prioritization to maximize operational efficiency.

The ERP system plays a pivotal role in the SW infrastructure by seamlessly integrating with the WMS and serving as a comprehensive business management solution. It facilitates direct communication and data exchange with the WMS, ensuring that critical information such as inventory levels, product information, and purchase orders are shared in real-time. Moreover, the ERP system enhances decision-making by offering data-driven insights and enables seamless coordination among various departments involved in warehouse operations. To enable seamless operation and efficient communication with the PI network, interconnectivity within the real system is essential. The ERP system is interconnected with the WMS, facilitating order request initiation and the transmission of quotes in response to perturbations coming from the network. Similarly, the WMS is interconnected with the WCS, ensuring that real-time stock information is relayed to the control system for optimized retrieval and storage processes. These integrated software enables effective coordination and control of warehouse operations within the π-store node, as well as efficient interactions and communications with the PI network.

In fact, the PI network is able to interact with the real system by initiating order requests, i.e. perturbations, through the ERP system. The real system responds to these requests by providing quotes, incorporating factors such as inventory availability, delivery schedules, and pricing information. Additionally, the PI network can request specific actions, such as the retrieval or storage of π-containers. The real system executes these actions based on the directives received from the ERP, passed to the WMS, and send to the WCS, which orchestrates the movement and operations of the automated equipment.

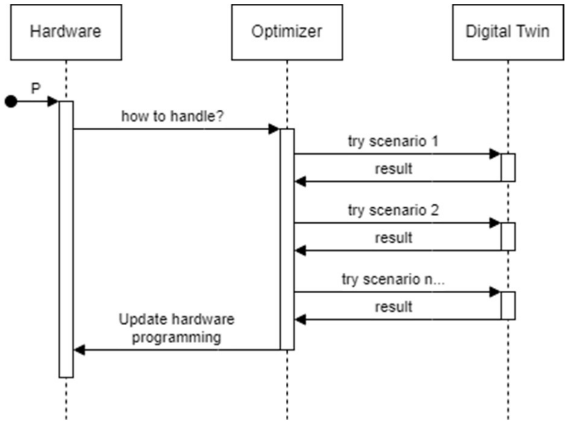

Fig. 4. Conceptual schema of the proposed model.

A simulation model replicating the functioning of the MLS was developed through the AnyLogic platform, and successively calibrated and validated based on the comparison of its performance with the one of the real system. The DT comprises both hardware and software components. The DT HW represents a virtual replica of the physical HW, while the DT SW includes a simplified version of the WMS and WCS. The connectivity between the real system and the DT plays a crucial role in enabling predictive and simulation-based analysis. For this reason, the DT SW is connected to the SW in the real system, allowing the loading of the current state of the warehouse operations. By simulating multiple stochastic scenarios, the DT could generate integrated forecasts that vary depending on the choices made and gradually communicate the best predicted solution to the physical machine based on the confirmed perturbations by the network. Figure 4 shows a conceptual framework of how multiple scenario testing can work. Upon the arrival of a perturbation (P) from the PI network, an optimizer attempts to update the programming on the DT. The DT simulates different scenarios based on the hardware state and sends the results back to the optimizer. Only when the optimizer finds the best solution can the HW be updated. Moreover, another feature of the DT is that it enables the prediction of the future state of the real system, which can be directly transmitted to the PI network for proactive decision-making.

V. DISCUSSION AND CONCLUSION

The proposed approach offers several advantages in the context of the π-store operations. Firstly, it enables real-time monitoring, allowing for improved synchronization with π-movers. This ensures that the operations of the π-store are aligned with the dynamic demands of the PI network. Additionally, the DT allows for the adjustment of operational parameters of the AS/RS system to effectively respond to real-time demand from the PI network. Lastly, it facilitates the evaluation of the efficiency of higher protocols implemented by the stakeholders of the PI network. These capabilities contribute to enhancing the overall performance and effectiveness of the π-store within the larger PI ecosystem.

Regarding the protocols of the PI, the types of information that could be exchanged between a PI-node and the PI network, have been examined. It can be concluded that the information that can be received and sent by the π-store node simulated differs between a strictly collaborative and a competitive model. In the first case, the exchange of information, i.e. perturbations, can be sufficient, while in the second case, transactions involving financial aspects of the individual node come into play. Based on this evidence, it can be stated that there is the need for a structure based on at least two layers to accommodate these different types of information.

By providing a concrete case study on a logistics laboratory, which serves as a π-store within the PI, it was demonstrated that the integration of a node's DT with the PI can enhance efficiency for both the node and the network.

In future works, the aim is to implement this approach through a simulator that captures real perturbations incoming from the PI, demonstrating the potential of this approach in a more quantitative way.

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