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INTEGRATING DYNAMIC DIGITAL TWINS: ENABLING REAL-TIME CONNECTIVITY FOR IOT AND VIRTUAL REALITY

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ABSTRACT

When Industry 4.0 technology is applied, it can increase resilience in production systems with interconnected machines and workers. As it is still evolving, research and implementation gaps due to issues such as costs, security, and a lack of use cases and domain expertise for enabling Digital Twins, need to be bridged. This paper proposes a framework connecting an Internet of Things platform with Digital Twin-compliant software based on ISO 23247. The simulation software provides cognitive support for the user who is immersed in the Digital Twin through Virtual Reality, and provides applications such as remote control and exploration of what-if scenarios. Connectivity with an Internet of Things platform facilitates real-time bi-directional communication, collaboration, monitoring, and assistance. A proof-of-concept use case based on an assembly line for a lab-scale drone factory was used for validation of the deployed Digital Twin based on ISO 23347.

1 INTRODUCTION

In recent years, the interest in Industry 4.0 technology within manufacturing systems has significantly increased. This is due to its capability to utilize big data in real-time, and facilitating communication and connectivity between digital and physical systems. This is imperative in today's rapidly changing markets, where increased resilience, responsiveness, and adaptiveness are critical to a company's chance for success (Schuh et al. 2020). Technologies such as Digital Twins (DTs) are considered to be key enablers of Industry 4.0, as they play a vital role in transforming traditional industries by offering a real-time connected digital representation of their real-world counterparts, enabling monitoring and remote control of manufacturing systems (Perno et al. 2022), and the exploration of a system's behaviour through simulation (Ariansyah et al. 2020). By incorporating Virtual Reality (VR) into the DT, the user is immersed and can navigate and understand the environment, shifting the DT towards a more user-oriented perspective (Cao et al. 2024). While DTs offer significant benefits in manufacturing systems and other industries, their value is not fully recognized in terms of reduced time to market, improved manufacturing equipment performance, and improved overall quality (Aaron Parrott 2017).

Previous research has consisted of general frameworks for DT applications ((Shao and Helu 2020a); (Yuchen et al. 2021), and there is a lack of domain-specific case studies, as well as insufficient research regarding evaluation- or metric-based implementation of DTs (Sharma et al. 2022). In support of standardizing DT implementation, the *ISO 23247 Digital Twin Framework for Manufacturing* standard was developed, concerning overview and general principles, reference architecture, digital representation, and information exchange (Shao and Helu 2020a). The paper posits that practical implementations of the DT concept using standardized frameworks can support scalable value creation, and the synchronization strategy is one of the main elements of DT implementation. The synchronization strategy regards an Internet of Things (IoT) platform, responsible for the simulation model's and real system's real-time connectivity. Consequently, the research question for this paper is:

- **RQ:** *How to use DT standards to support the integration of simulation software and an IoT platform establishing a real-time connectivity?*

To answer the question, the main objective of this paper is to propose a practical example of the real-time connectivity implementation supported by the ISO 23247 framework. This example should be considered as an instance of DT implementation, not a recommendation nor a standard itself. In order to achieve this main objective, the authors will develop an integrated DT reference architecture applying the ISO 23247 standard framework, develop a VR-integrated simulation model to represent a lab-scale real system, propose an architecture to establish connectivity between a simulation model and its real system and demonstrate the real-time connectivity of DTs through a proof-of-concept use case.

In section 2, the paper describes the connection between DTs, VR, and IoT concepts to support a methodology described in section 3. The methodology is based on the proposed framework for DT connectivity and explains how it will be implemented in practical use cases. The results are presented and discussed in section 4, showcasing a practical case implemented in a lab-scale drone factory connected in real-time. Section 5 presents the conclusions with recommendations for future research.

2 THEORETICAL BACKGROUND

To position the study into the larger scope, a theoretical background on the three interconnected topics serves as a base for this paper. The topics are DTs and their functions, including benefits and different perspectives of implementation; VR and simulation, including terms and applications, and IoT systems including the components and configurations.

2.1 Digital Twins

The concept of a DTs (Grieves 2014) serves as a dynamic mapping between physical objects and simulation models, converging physical and cyber layers of a system. This solution facilitates interconnection, interaction, control, and management on the shop-floor level, supporting the advancement of smart manufacturing practices (Tao and Zhang 2017). One straightforward benefit of DT is assessing systemic issues in complex systems, which often emerge due to human interactions during operations (Grieves and Vickers 2017). Furthermore, DT implementations effectively enable data-driven and smart manufacturing, setting the foundation for the other Industry 4.0 technologies (Qi and Tao 2018).

The literature on DT presents work focusing on different perspectives of its implementations, from the catalogue of system architecture patterns in DT design (Tekinerdogan and Verdouw 2020) to the detailing of scope and structural design requirements for DTs (Shao and Helu 2020b). The need led to the development of the ISO 23247 standard for DTs, which addresses the interdisciplinary challenges of DT development providing a framework for manufacturing DT implementations (Shao et al. 2023).

A broad study on DT applications in the manufacturing field is provided by Jiang et al. (2021) showcasing applications in process monitoring, life prediction, and asset management that demonstrate significant operational efficiencies (Jiang et al. 2021). Other practical cases of the ISO 23247 implementations are given in this section, where the framework has been applied to model DTs for flexible manufacturing cells, emphasizing key features and product lifecycle integration (Wallner et al. 2023). Additionally, it was used to detail an architecture for a wire arc additive manufacturing DT. Although it was not fully implemented, the benefits were assessed as a clear potential to enhance integration and real-time decision-making (Kim et al. 2022).

The main functions of DTs are supporting decision-making, enhancing visibility, optimizing operations, and increasing resilience to disruptions (Lugaresi et al. 2023). Credibility challenges in manufacturing

DTs lead to the need to emphasize the importance of verification, validation, and continuously maintaining credibility to ensure trust and reliability (Shao et al. 2023). The benefits of integrating immersive VR with DTs, such as improved visualization and interaction, can be achieved while addressing challenges such as complex VR design, better hardware controls, and communication strategies (Pirker et al. 2022). These insights show the DTs' transformative potential across various sectors, addressing challenges such as in unifying communication interfaces and lacking efficient modelling frameworks (Sun et al. 2022).

2.2 Simulation and Virtual Reality

Simulation and VR are key technologies revolutionizing various industries, particularly for manufacturing. Simulation involves creating a digital representation of a real system or process to analyze its behavior or performance. It is instrumental in optimizing production systems, as it allows for scenario testing and decision-making based on predicted outcomes (Ottogalli et al. 2019). VR, on the other hand, refers to an interactive computer-generated experience that simulates environments or situations, often using immersive technologies.

In a literature review (Pirker et al. 2022), with a focus on the convergence of these concepts, it was noted that integrating VR technology into DT applications can enhance visualization, interaction, and user experience. In manufacturing optimization, VR can be used for simulation of real-world production processes, enabling better decision-making. VR tools like HTC VIVE or Oculus Rift described in the use case (Robert et al. 2019), can facilitate real-time optimization by streaming high-resolution graphical representations of simulation models.

2.3 IoT Systems

An IoT system enables connectivity between the physical system and the simulation model in a DT with the help of connected devices such as sensors and actuators. The collected data is stored and used by applications for different purposes such as predictive maintenance, analysis, monitoring, control and optimization (Guth et al. 2018). However, a significant challenge within DT frameworks is establishing effective connectivity between virtual models and physical systems. This connectivity involves setting up communication protocols that enable synchronous interactions between a simulation model and its physical counterpart, such as OPC UA, an industry-standard communication protocol (OPC Foundation 2024), CODESYS, an automation software for controlling and providing access to PLCs (CODESYS GmbH 2024), or RESTful APIs/MQTT for sending and receiving messages within the system (Guth et al. 2016). The reason behind the technical challenges is the lack of domain expertise and knowledge regarding communication and information technologies (Chen et al. 2024).

To describe an IoT system, there exists a number of IoT architecture frameworks provided by both the research and manufacturing industry. (IEE 2020) defines a comprehensive framework standard including the architecture development process and application domains, the 3- or 5-layered models bring a more simplified architecture solution (Guth et al. 2016), while (Swamy and Kota 2020) provides a hybrid architecture with examples of the varied components of the IoT system.

The architecture used for describing the different components is based on the IoT reference architecture proposed by (Domínguez-Bolaño et al. 2022), which addresses crucial components for this paper. It comprises sensors, actuators, the IoT platform, a communications network, an IoT gateway, applications, security, and management. The sensors capture information supplied to the user, to control the system by using the actuators, which convert the command to a physical action based on a request from the IoT platform. IoT platforms, gateway components, and communication networks based on various communication standards provide communication between sensors and actuators. The elements supporting the communications are the middleware component IoT gateway, the data layer protocol and the prescribed data format. The IoT platform is responsible for managing the devices, handling data storage and analytics, and supporting applications, where the software uses the input and output from devices to perform tasks and services.

Security is maintained by encrypting and monitoring keys and certificates, whereas management regards system performance and configuration, networks, fault management, and service updates. To facilitate successful real-time connectivity with these components, a methodology for the integration is required to solve application gaps such as standardization, interoperability, data acquisition, and poorly constructed user interfaces (Chen et al. 2024), which is presented in the following section.

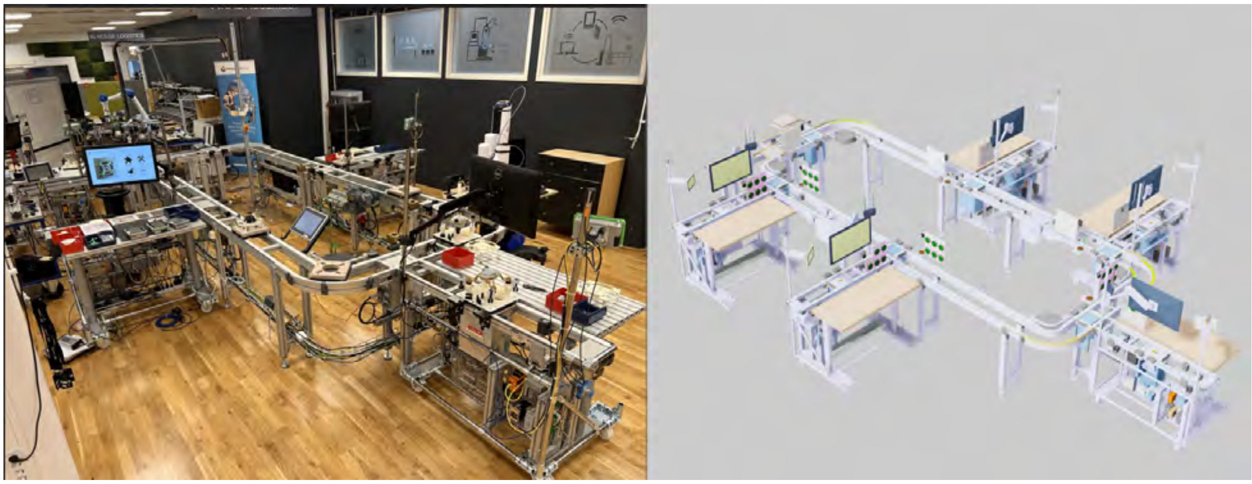
3 METHODS

The study aims to realize real-time connectivity between the digital simulation software and the physical production system, using VR as a human-centric approach, allowing designing, testing, analyzing, and optimizing manufacturing processes in a virtual environment. The following sections will introduce the real system and its elements, for which the proof-of-concept use case has been developed and tested to validate the proposed framework, with industry input in the form of recommended best practices.

3.1 Real System Description - Proof of Concept

The physical system refers to the SII lab in Lindholmen, Gothenburg, which serves as a platform for research, training, and the demonstration of smart industrial production in the context of Industry 4.0 and digital transformation, providing the opportunity to validate the connectivity in real-time with embedded sensors and the provided IoT platform and simulation software. It is a lab-scale drone factory including a production line where pallets transport the drones on a conveyor belt. Figure 1 displays the real system positioned next to the simulation model, where the conveyor belt connects six branch assembly stations, including a buffer, and an Autonomous Mobile Robot (AMR). Additionally, the lab employs in-house logistics to manage the transformation of raw materials and products, both internally and externally through the main conveyor (Taylor et al. 2021).

The lab-scale drone factory is controlled by Programmable Logic Controllers (PLCs), with I/O (Input/Output) units distributed across each station. Sensors at stations detect the arrival of pallets, whereas the pallets are equipped with RFID (Radio Frequency Identification). The docking station's I/O setup also includes two sensors for pallet sensing and another two for monitoring elevator transfers, facilitating the vertical movement of pallets between the main conveyor and the workstation. Additionally, there is a sensor managing the queue stop (Stena Industry Innovation Laboratory 2024).



(a) SII Lab - real system

(b) Emulate3D - simulation model

Figure 1: Real and Virtual systems of the smart production system

3.2 ISO 23247 Standard Framework For Developing Digital Twins

In this section, the adopted framework for implementing a DT with real-time connectivity is described, based on the ISO 23247 standard to support the connectivity between the physical system, the simulation model, and VR for human-centric interaction (Shao et al. 2021). The framework comprises four main parts: (1) Overview and General Principles, which define the physical systems as Observable Manufacturing Elements (OMEs) that need to be twinned; (2) Reference Architecture, which consists of four main domains: OME Domain, Data Collection and Device Control Domain, Core (DT) Domain, and User Domain; (3) Digital Representation, which describes the basic information attributes for typical OMEs, including both static and dynamic information; and (4) Information Exchange, which outlines the technical requirements for the exchange of information between entities within the framework.

These components provide guidelines for defining the scope and objectives, setting simulation model requirements, implementing a generic reference architecture, and supporting information synchronization between a DT and its physical counterpart. This paper primarily focuses on part two of the ISO 23247 standard to support the concept of connectivity, as the excluded parts were completed before implementation. This approach will be instantiated in the next section for the implemented use case.

Existing standards in data collection, data security, information modelling, system modelling, simulation, visualization, and networking, which were originally developed for various general or specific purposes, can also be applied to support digital twin applications and achieve similar results but not tested in this study (Shao et al. 2021). For instance, the Asset Administration Shell (AAS) serves as a standard for the DTs standardization and interoperability framework, and it can be adapted for further DTs use cases (George, Henry 2017).

3.3 Virtual Reality Integrated Simulation Solution

Emulate3D (Rockwell Automation, Milwaukee, USA), a Computer-Aided Design (CAD) software, was utilized for constructing the simulation model of the lab-scale drone factory. The software includes a library of built-in catalogues and pre-modelled components that feature manufacturing equipment components such as conveyors, robots, loads, stairs and walls. The drone product CAD files can be imported where the aspects are automatically added, and together with functions such as sensors and buttons, the virtual model can be used for simulation, emulation or demonstration, allowing users to test the connectivity in VR with the HTC VIVE device to enable human-centric interaction.

Furthermore, the simulation software integrates with various communication protocols, such as Siemens, CODESYS, Allen Bradley, and OPC UA protocols, using Tags to represent the physical system's I/O points. Emulate3D's tags are defined in the IO Browser, which displays currently loaded tags, their definition and binding, and connects the tags to the controller via a Tag Server. To ensure the effectiveness of the simulation, simple representations of physical objects should be implemented, together with a reduction of unnecessary physical properties.

3.4 Construction of IoT Architecture

The IoT platform Thingworx (PTC, Boston, USA), a licensed enterprise solution, enables connectivity using a modular approach for establishing the corresponding data model to provide feasible scalability. Data is collected, stored and visualized by using the Thingworx Foundation Server, and applications are built with Things, Thing Templates and Thing Shapes. A Thing represents physical devices, products, systems, processes, assets and people. It is based on a Thing Template that determines a set of Properties and Services, providing the possibility of duplicating Things. The Thing Shape describes the relations between items using Services, Properties, Events, and Subscriptions, where Thing Templates can inherit Properties and business logic, providing scalable maintenance and updates to the platform (PTC Community Management 2022).

The middleware Kepware enables encrypted communication and a limited amount of traffic between the different layers of firewalls in the operations network, constricting access control while facilitating remote management and configuration of connected devices within the factory's network. The middleware can also act as an OPC UA server, providing real-time and bi-directional communications between the model and Kepware. For the communication between Kepware and the real system, CODESYS is utilized.

4 CONCEPTUAL DESIGN AND RESULTS

In this section, results and the conceptual design are presented and discussed, following the completion of objectives with the reference architecture based on ISO 23247, presentation of the VR simulation model, description of the integration of the IoT platform and simulation model, and the connectivity realized with the help of a proof of concept use case.

4.1 Framework Instantiated Based on ISO 23247 Practical Implementation

Figure 2 shows the instantiated functional view of the ISO 23247 reference architecture for the lab-scale drone factory DT implementation. As mentioned in Section 3, the standard framework consists of four parts, and only the reference architecture part is used in this research. Each domain in the reference architecture comprises a logical group of tasks and functions performed by the functional entities (FEs). The OMEs are the physical elements, where data are collected from sources such as CAD files, sensors, and PLCs. The core DT entity manages the simulation modelling, VR modelling, connectivity, synchronization, interoperability, etc. as described in section 3, where the lab-scale drone factory DT performs real-time monitoring and PLC control. User interfaces provided by the user entity enable interaction with the core entity, with VR controllers and the ThingWorx IoT platform representing the user entity in this use case. The reference architecture supports the development of DTs by displaying the elements vital for the integration and showcasing the interconnectivity by only including parts relevant to this paper.

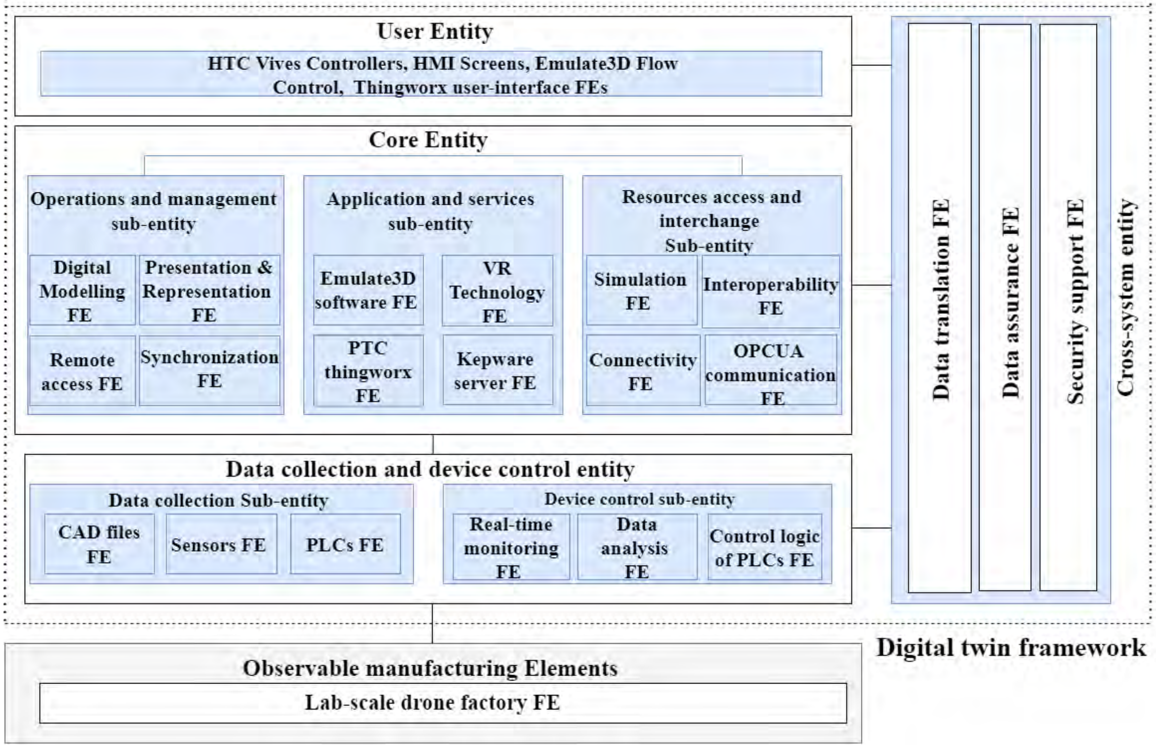


Figure 2: Functional view of the instantiated reference architecture (Shao et al. 2021)

4.2 Virtual Reality integrated Simulation Model

The VR functionality is embedded in Emulate3D software to stream the virtual system's human perspective. The functions are the basis for further applications such as virtual operator training and commissioning. The interactions are pre-edited in the desktop view, with pallets, drones, and kits functioning as interactable, grabbable and with physical properties such as gravity and friction. By activating the button in the VR scene and PLC control system of the physical world, the virtual control is enabled and can be accessed directly from the virtual scene with a headset, where the human perspective is visualized in Figure 3.

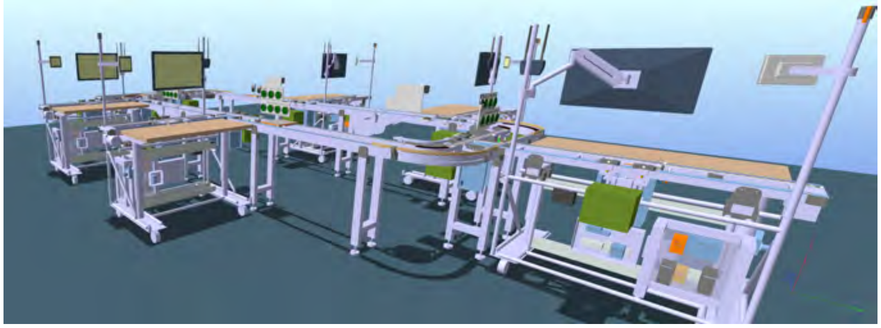


Figure 3: Human perspective in VR environment to control the DT system

4.3 Integration of Simulation model and IoT platform

When concluding the models for the simulation and the IoT platform, the connection is upheld within the Kepware server. An application key is utilized to connect and monitor the equipment in the lab-scale drone factory, which authenticates the data sent to Thingworx, while also allowing the server to whitelist selected IP addresses (PTC Community Management 2023). For connecting the simulation model to the Kepware server, an OPC UA server was created in Kepware, which enables client/server architecture while providing secure and easy data transfers through firewalls. Figure 4 visualizes the structure for communications enabled by the constructed connectivity, where the simulation model is integrated with the real system through the IoT platform with Kepware, representing the DT, and the user is immersed in the model through VR in real-time, enabling interaction with the DT.

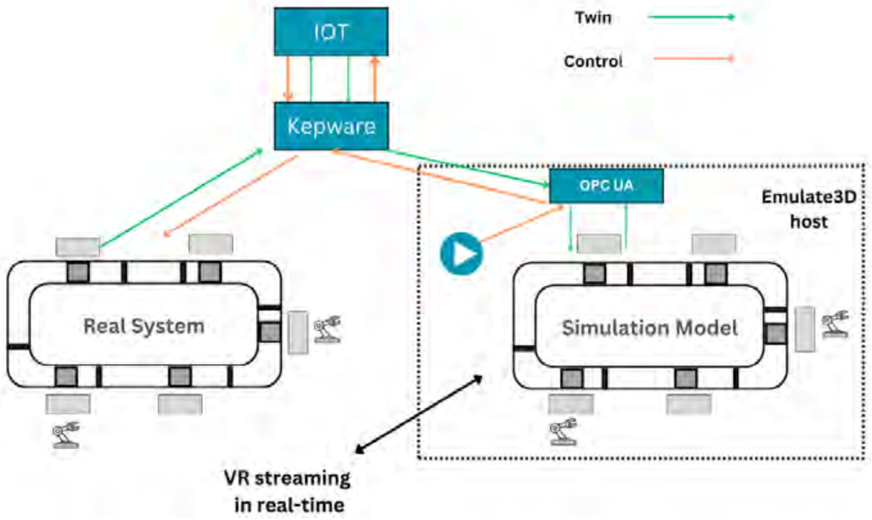
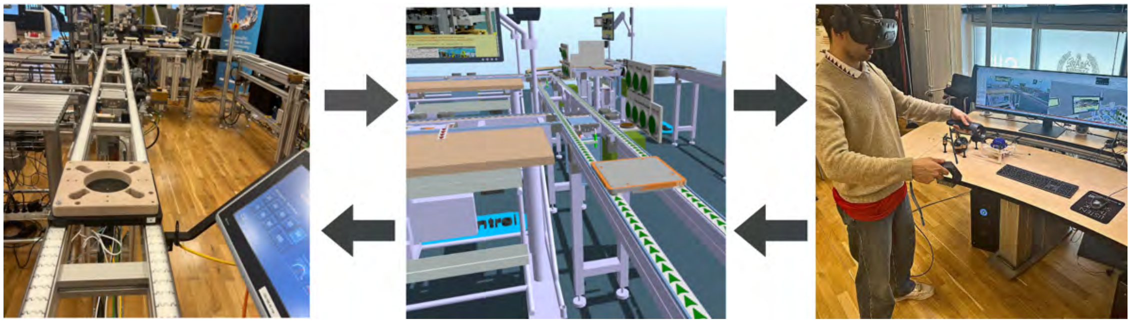


Figure 4: Communication between the real system and simulation software (Erdal and Gubartalla 2024)

As the real system serves as the master system, the simulation model needs to initiate a mission by placing a request. The request is sent through the Kepware server with the help of the communication standard OPC UA. Consequently, the request is delivered to Thingworx, which checks if the mission is available, and sends it to the correct station in the lab-scale drone factory through CODESYS, which has the PLCs directly connected to the server. The real system returns the confirmation to the simulation model before executing the mission. With the selected configurations, the communication between the IoT system and the simulation model results in approximately a one-second latency. As discussed by (Lopes et al. 2023), this occurrence will affect the updates of real-time data, but depending on the context, the configurations might need to be altered. For the proof of concept use case, monitoring and control will be the main applications for the DT, and the latency must then be minimised to ensure synchronization between the real system and the simulation model.

4.4 Use Case Connectivity between IoT Platform and Digital Twin Software

The connectivity is validated through the proof-of-concept use case, by visually ensuring the behavior of the physical and VR simulation systems correspond when selecting a mission by pressing a push button, where the synchronized events in the real system, simulation model and for the VR User can be seen in Figure 5.



(a) Real System (b) Simulation Model in VR (c) VR-User

Figure 5: Visualization of the bi-directional connectivity through VR

Table 1 provides a detailed description of the use case, where the selected mission is to request the drone pallet to pass a docking station. The sensor that hinders the passage deactivates and the pallet can proceed to the next station. To make a request, the user has several options. They can use the HTC Vive headset and controllers to virtually make the request by pressing a connected virtual push button, placing the request within Thingworx's user interface, or directly communicating with the PLC through the HMI screen. The objective is to ultimately have the simulated pallet mirror the behavior of the physical pallet, in terms of both speed and position. However, the RFID tags in place have not yet been incorporated into the DT which is recommended for future research, to develop a system that updates the pallet's position in real-time, while adjusting it to the communication latency.

The use case with the established connectivity is proven to be functional as the push buttons are operative and can be used to control both the simulation model and the real system. In terms of the focus of this proof of concept use case is the operation phase in terms of lifecycle perspective. It could also easily be applied to the design phase as in virtual commissioning, or for the maintenance phase, as implementing AI analysis is beneficial as it aids in evaluating machine health, e.g. preventive maintenance, or exploration of what-if scenarios (Taylor et al. 2021). Furthermore, the proof of concept use case establishes a real-time connected DT where communication and control are bi-directional, with future possible applications such as remote control and monitoring with VR accessibility, which could be potential architecture to support early fault detection, virtual commissioning, training operators, and optimization of production times and throughput.

VR is integrated into the system through the simulation software that supplies both the PLC protocol and VR streaming function and has been regarded as the key to making the VR-integrated DT successful. To further evaluate its benefits on social sustainability such as cognitive ergonomics, better decision-making support, and pedagogy in the virtual training, the VR-integrated DT demo should be further developed into a use case and experiment, along with user investigation. The use case shown in this study is to showcase that, following the standardized ISO 23247, the DT case could be enabled in the specific simulation software and physical system, while its benefits and further safety risks are still to be explored, and could be identified as a future study.

Table 1: A summary of real-time connectivity use case.

ID	SII lab Scale Drone Factory
Use case name	Connectivity between IoT and simulation software
Application field	Smart Manufacturing
Cycle stage(s)/phase(s) coverage	Production
Status	TRL 7 Demonstration in representative environment
Scope	Perform a real-time connectivity in DT
Initial (Problem) situation	Within the domain of DT frameworks, a fundamental challenge lies in establishing connectivity between the virtual and physical systems. In this context, connectivity refers to the communication protocol enabling synchronous interaction between a virtual model and its physical counterpart. The goal is to facilitate real-time control and movements of the physical entities while ensuring that the DT accurately replicates these actions. The problem is to address how this data connection operates simulation-based DT and the physical system (lab-scale drone factory) ensuring a connection capable of bidirectional data transfer.
Objectives	Implement the real-time connectivity demonstrator in a physical system
Short description	To demonstrate the developed connectivity, missions from PLCs have been virtually created in Emulate3D, represented as push buttons. The logic mimics the real system's progressions. The selected mission is Pass Docking Station, where the user can place the request either in the simulation software, at the IoT platform or directly with the HMI screens belonging to the real system. The blocked drone pallet can then pass the docking station, where the mission is replicated in the simulation model in real time.
Stakeholders	Manufacturing shop floor personnel, management, researchers
Key technologies	Automation, data analytics, simulation, VR, IoT

5 CONCLUSIONS

The paper demonstrates how connectivity in dynamic DTs can potentially drive improvements in system operations and decision-making processes with real-time simulation, analysis and monitoring, with VR integrated to highlight the human-centric perspective in the technology. It presents a reference architecture supporting the integration of IoT platforms with 3D simulation software based on the ISO 23247 DT Framework. The objective is to bridge the current gaps in pragmatic implementation strategies and the verification of frameworks, which was provided by the integration of the simulation model and the IoT platform.

To further scale the deployed DT, the IoT solution requires further development, such as several layers of Kepware servers to ensure secure communications throughout the organization, and additional handshakes in the communication, such as checking if a mission has been completed. For a fully synchronized DT, all sensors and actuators need to be connected, where in this case only selected sensors belonging to specific push buttons are connected. Together with applying a purpose to the DT, for instance, analysis supported by Artificial Intelligence of current and future systems will bring business value to the DT and will be the matter for future research.

As for a general takeaway regarding the implementation of a DT for monitoring and control of manual assembly, the security issues and the purpose of the DT need to be investigated before development. For instance, a moving assembly line controlled remotely can risk the safety of operators if they are within the vicinity of the assembly line when a request is being executed. To ensure the safety of operators, pressure-sensitive mats can be installed blocking control of the assembly line remotely when an operator is standing on it. For this specific use case, the virtual platform should have strict authority access and should be mainly operated as a monitoring system, emergency maintenance support, and remote control system when no operators are working in the workstation area. To better understand how to realize the benefits of real-time connectivity, further studies with concrete use cases should be designed and explored with multiple stakeholders, including operators, engineers, and managers. However, regardless of the risk, implementing DTs correctly in the factory will still be the key infrastructure to accelerate the digital transformation of the industry.

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DISCLAIMER

Specific commercial products and systems are identified in this paper to facilitate understanding. Such identification does not imply that these software systems are necessarily the best available for the purpose. No approval or endorsement of any commercial product by NIST is intended or implied.

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