Setting up a Digital Twin for Real-Time Remote Monitoring of a Cyber-Physical System

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Abstract: With the advent of Industry 4.0, Digital Twin technology has emerged as a pivotal advancement in industrial applications. It enables the creation of a precise digital replica of physical systems. These Digital Twins can be used throughout the entire lifecycle of the physical system, from initial design stages through to operation and disposal. They facilitate design optimization and enable simulations under realistic conditions. This paper presents a case study centered around a UR3e robot, where a Digital Twin is developed using Emulate3D. Communication between its physical and digital counterparts is established. This setup thus enables synchronized operation: when the physical robot executes a program, the Digital Twin replicates the actions and responses, and vice versa. This represents the first steps towards the use of Digital Twin technology for real-time remote monitoring of the robot.

1 INTRODUCTION

The rise of Industry 4.0 has been marked by significant technological advancements, among which the concept of Digital Twins (DT) stands out as an innovative fusion of physical and digital realms. Initially introduced by Michael Grieves in 2002, Digital Twin technology has evolved into a fundamental tool across various industrial sectors, including manufacturing, aerospace, automotive, and healthcare. These virtual models replicate not only the physical appearance but also the dynamic behavior of their real-world counterparts, providing a critical interface for real-time monitoring, diagnostics, and prognostics (Kritzinger et al., 2018; Barricelli et al., 2019).

Digital Twins leverage the power of IoT sensors, artificial intelligence, and machine learning to create live, evolving simulations. These simulations enable continuous monitoring and predictive maintenance, thus enhancing operational efficiency and decision-making capabilities (Negri et al., 2017; Tao et al., 2018). For example, in the automotive and aerospace industries, Digital Twins facilitate the simulation of vehicle and aircraft performance under varied operational conditions. This capability significantly reduces reliance on physical prototypes, thereby decreasing costs and enhancing the safety and reliability of these high-stakes products (Jones et al., 2020).

In the manufacturing sector, Digital Twins prove instrumental in optimizing production lines. They offer detailed insights into process inefficiencies, bottlenecks, and potential failures, enabling preventive adjustments to maintain continuous and efficient production (Kamble et al., 2018; Lu et al., 2020). Moreover, Digital Twins are crucial in the energy sector, where they are used to model and optimize the operations of complex systems such as wind turbines and power plants. Their application in this sector promotes sustainability and reduces operational risks (Wang et al., 2017; Schleich et al., 2017).

Another significant application of Digital Twins is in the realm of maintenance. Traditional maintenance strategies, which are often reactive or scheduled at predetermined intervals, can lead to unnecessary downtime and unexpected equipment failures. Digital Twins facilitate a shift towards predictive maintenance, where the condition of equipment is continuously assessed to schedule maintenance just before potential failures are anticipated. This proactive approach not only minimizes downtime but also extends the lifespan of equipment, ensuring that operations run smoothly and costs are kept under con-

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trol (Söderberg et al., 2017; Schluse et al., 2018).

Furthermore, Digital Twins significantly aid in the customization and testing of products in a virtual environment before actual production, leading to innovations in product design and functionality. They also play a crucial role in training and simulation, where operators are trained on virtual models, thus reducing training costs and exposure to hazardous environments (Glaessgen and Stargel, 2012).

For those interested in more in-depth examples and broader applications of Digital Twins, comprehensive review articles provide extensive discussions on the impacts and implementations of Digital Twin technologies across various industrial sectors (Khan and Turowski, 2016; Tao et al., 2018).

This study focuses on the use of Digital Twin for real-time remote monitoring of robots. To achieve this, real-time communication between the physical and digital twin must be established. In addition, the twins should be able to replicate in real-time each other's behavior. Moreover, the architecture should allow an operator to remotely take control of the physical twin *via* its digital twin. This paper presents the first steps towards this goal. For this purpose, it presents a practical application involving a UR3e robot and the Emulate3D software. First, the global architecture of the Digital Twin will be described, followed by a detailed discussion of a practical test case. This work aims to demonstrate the capabilities of Digital Twins in enhancing real-time system monitoring and operational tuning for improved responsiveness and adaptability.

2 GLOBAL ARCHITECTURE

The implementation of the Digital Twin technology in this study focuses on a compact robotic system equipped with a grip and a camera. In addition, a conveyor adjacent to the robot transports objects within its reach. This section will describe the architecture of both the Physical Twin and the Digital Twin.

The UR3e robot (Universal Robot, 2024), a small industrial robot arm cited frequently in academic and industrial applications, is known for its versatility and ease of use. It comes with a teach pendant that allows and simplifies the programming and control of the robot, making it suitable for a wide range of tasks from assembly to welding. Its affordability, compact size, and adaptability make it an ideal candidate for experimental and educational projects in academic settings (Wolniakowski et al., 2021; Mustafin et al., 2023; Abbyasov et al., 2024).

A review conducted in (Konstantinov et al., 2023) evaluated various Digital Twin softwares according to the Industrial Internet Consortium's criteria (Yi et al., 2015). In this study, Emulate3D and Visual Components emerged as leaders due to their advanced capabilities and compliance with numerous criteria. In this work, the software used is Emulate3D. To the authors' knowledge, this software has been scarcely used to develop Digital Twins and it has mostly been used for simulation purposes. For example, McGinnis and his co-authors (McGinnis et al., 2021) have used the software to produce a physic-based model of a robotic consolidation cell. This allowed the authors to develop realistic cycle time distributions. In addition, in their work Zhao and his co-authors (Zhao et al., 2022) used Emulate3D to simulate and optimize the design of a large scale mobile phone assembly production line. For this work, Emulate3D was principally used as a simulation tool. It allowed retrieving various parameters, thus enabling the computation of defined KPIs and identifying potential bottlenecks. Nevertheless, to our best knowledge, no Digital Twin with real-time communication has been implemented.

2.1 Physical Twin (PT)

The physical setup revolves around a UR3e robot equipped with a suction gripper from Schmalz Vacuum and a high-definition camera from SICK (see Table 1 for more details). The system's versatility is enhanced by a programmable interface provided on a tablet that accompanies the robot, allowing control and programming capabilities. Furthermore, the assembly includes a conveyor system managed via a Human-Machine Interface (HMI), complemented by an optical sensor that detects the objects on the conveyor.

This setup is controlled through a Programmable Logic Controller (PLC) from Schneider, which ensures communication and operational synchronization among the various components. The integration of these components is facilitated by an IO-LINK system that guarantees robust data transmission and system reliability.

The communication dynamics within this system are depicted in Figure 1, illustrating how the various elements interact within the network:

1. The camera and suction gripper are controlled by the control interface of the robot. Using this interface it is possible to activate or deactivate the gripper, as well as to detect loads using the camera (this detection is programmed *via* SOPASair but it falls out of the scope of this work).
2. The UR3e robot communicates essential operational data such as joints' angle, tool position, suc-

tion gripper status to the PLC. In addition, some channels are open so that it can receive data from the PLC.

3. Data from the optical sensor about the status of the conveyor (blocked or cleared) is sent directly to the PLC, enabling real-time adjustments.
4. The conveyor sends its status as well as its speed to the PLC, and the PLC can be programmed to change it.
5. The HMI plays a crucial role in visualizing the status of the optical sensor and allows operators to adjust the conveyor settings directly.

Figure 2 captures the experimental setup in a real-world scenario, visually representing the integration and placement of different components within the system.

Table 1: Hardware setup.

Component	Supplier	Model
Robot	Universal Robots	UR3e
Camera	SICK	InspectorP62x
Gripper	Schmalz	Vacuum ECBPMi
Conveyor	Norelem	95300
Optical sensor	IFM	O8H216
PLC	Schneider	M251MESE
IO-Link	IO-Link	AL1342

2.2 Digital Twin (DT)

In this project, the Digital Twin is built using the Emulate3D software, a powerful tool that allows for the recreation of the Physical Twin using detailed CAD models. Emulate3D's advanced physical engine facilitates the precise mimicking of the physical behaviors observed in real-world settings, thus providing an authentic and dynamic simulation environment (see Table 2).

In this study, the CAD models from the different parts of interest (namely the UR3e robot, the suction gripper and the conveyor) were taken from their respective suppliers. The CAD model for the support plate was designed manually. Moreover, to reproduce the behavior of the physical optical sensor, a sensor element from the software has been added its localization.

During the assembly of these components within Emulate3D, attention to detail was paid to ensure that all parts were positioned in the same configuration as their physical counterparts (see Figs. 2 and 3). Using the software's tools, the kinematic joints were reproduced, thus recreating the dynamic interactions between various parts of the assembly. Special attention was paid to input accurate mechanical properties into the software, such as the joints' angle limits, speed limits, and acceleration limits, to ensure the Digital Twin's performance closely matches that of the Physical Twin.

Table 2: Software used.

Software	
Automation software	Machine Expert 2.0
Camera software	SOPASair
Digital Twin software	Emulate3D 2022

Emulate3D's functionality extends beyond mere simulation; it is equipped to facilitate robust communication with Programmable Logic Controllers (PLCs) using protocols such as Modbus. This is critical for real-time data exchange between the Digital Twin and its physical counterpart, enabling synchronized operations and adjustments. Moreover, by establishing a secure network connection, the system enhances the feasibility of remote interactions between the two twins. Thus maximizing the utility of the Digital Twin for remote monitoring and control applications.

3 TEST CASE STUDY

The advent of Digital Twin technology leads to new opportunities for enhancing remote monitoring and maintenance processes within industrial settings. The capability of Digital Twins to accurately replicate and simulate physical systems presents an innovative approach to handling incidents on production lines.

Traditionally, when an incident occurs, it necessitates the stoppage of production activities and waiting for an on-site intervention. This approach often leads to significant downtime and loss of productivity. However, with the integration of Digital Twin technology, these challenges can be addressed more efficiently. Indeed, a Digital Twin allows for the detailed replay and analysis of the events that led to the incident. This not only aids in swiftly identifying the causes of issues on the production line but also helps the planning of necessary repairs and interventions without the immediate need for on-site presence.

Furthermore, using the detailed data from the actual on-site conditions, engineers can use the Digital Twin to perform simulations to find new, optimal operating parameters. This process ensures that once the production line is ready to restart, it operates under the best possible conditions, minimizing the likelihood of recurring issues.

Moreover, in scenarios where adjustments to the production processes are required, Digital Twin tech-

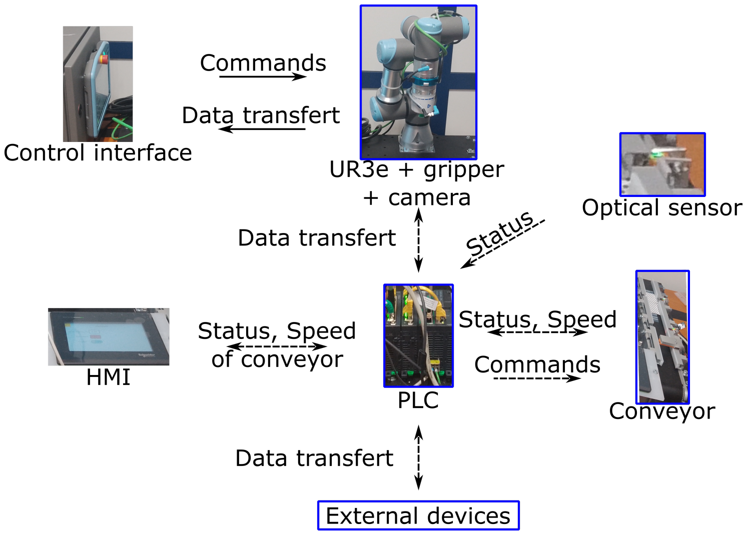

Figure 1: Schematic of the different communications for the Physical Twin. The dashed lines represent communications *via* the IO-Link. The blue squares depict the elements that constitute the Physical Twin.

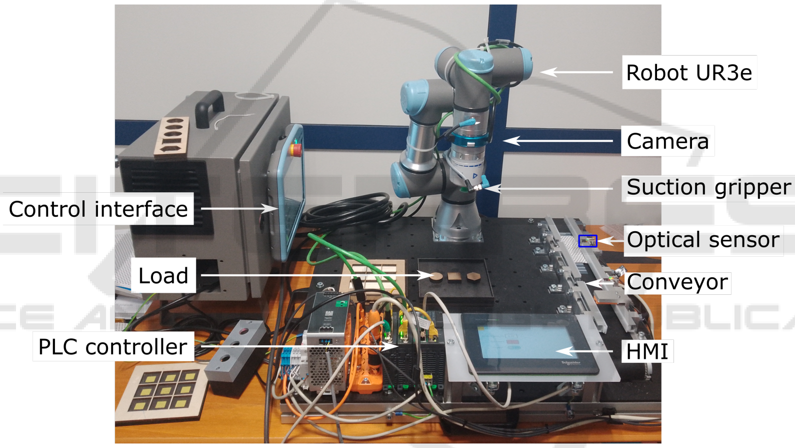

Figure 2: Experimental setup of the robot in the real world.

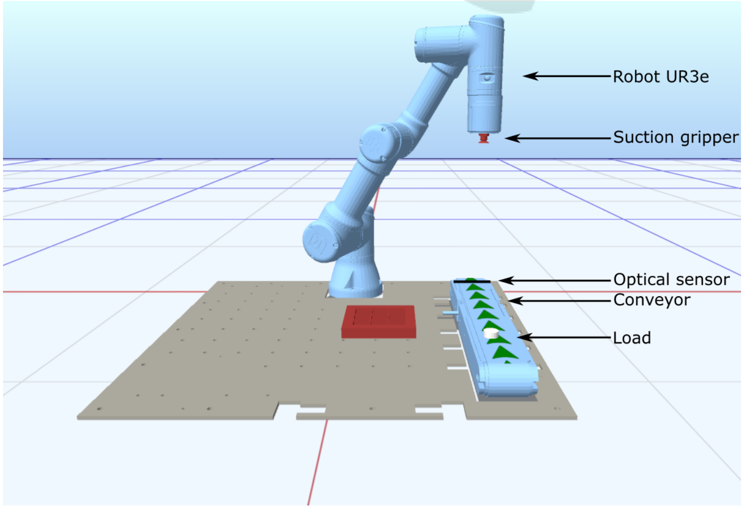

Figure 3: Comprehensive digital setup of the robot in Emulate3D, illustrating the detailed configuration and component integration.

nology enables the remote reprogramming of the production line. This functionality is particularly crucial as it allows for the continuation of operations, even if at a reduced capacity, thus significantly mitigating the impact of downtime and minimizing operational losses.

The test case study presented here is built upon the physical setup described earlier. It involves a scenario where objects, transported via a conveyor, are identified by the camera system and then handled by a robot, which sorts them into their designated containers. This practical application is designed to demonstrate the initial steps towards implementing real-time monitoring and adaptive control using a Digital Twin.

The approach to achieving effective real-time monitoring with a Digital Twin can be decomposed into two main stages:

1. Synchronization of the Digital Twin with the Physical Twin. This stage involves setting up the Digital Twin to accurately follow and replicate the real-time actions and statuses of the Physical Twin. This synchronization is crucial for ensuring that the Digital Twin provides a faithful and up-to-date reflection of the physical setup, allowing for immediate and accurate response strategies.
2. Enabling the Physical Twin to follow adjustments made in the Digital Twin. Once the initial synchronization is achieved, the next step involves adapting the system so that changes or optimizations suggested by simulations in the Digital Twin can be applied back to the Physical Twin. This bi-directional communication ensures that any enhancements or modifications obtained from the Digital Twin's simulations are effectively implemented in the physical setup, enhancing operational efficiency and adaptability.

3.1 DT Following PT

Achieving real-time remote monitoring involves ensuring that the Digital Twin can accurately replicate the actions and status of the Physical Twin. This section details the initial phase of this process.

The first step in this synchronization process involves programming the Programmable Logic Controller (PLC) to halt the conveyor system when the optical sensor detects an object. The behavior of the robot is then programmed using its control interface and the associated programming module. The programmed behavior sequence is as follows:

- **Initialization:** The robot is set to a default position, ready to start the operation cycle.
- **Object Detection:** If the conveyor stops, the robot uses its camera to detect the object on the conveyor.
- **Interaction:** After detecting the object, the robot moves to the object's location, activates the gripper to secure the object, and then moves it to its designated target location.
- **Release and Reset:** After placing the object, the gripper is deactivated, and the robot returns to its initial position.
- **Idle State:** If the conveyor does not stop, the robot remains in a waiting state, ready to react to the next trigger.

Emulate3D, the software used for the Digital Twin, supports robust communication with PLCs. This feature allows for the transfer of operational data from the Physical Twin to the Digital Twin in real-time. In what follows, the communications needed for the DT to mimic in real-time the PT are described:

- **Robot Position:** The robot position in the Digital Twin can be obtained by using the joints' angles. They are retrieved by the software using the ModBus protocol. To ensure good agreements, the angles are rounded in milli-radians.
- **Conveyor Status:** The software retrieves the conveyor status and speed using the same protocol. The status is a simple boolean, and the speed is retrieved in rounded mm/s.
- **Gripper Status:** The software also retrieves the gripper's status. The status is a simple boolean.
- **Sensor Status and Object Creation:** Similarly to the other part's status, the sensor's status is a boolean retrieved by the software. In addition, as soon as the gripper is activated, an object is created on the conveyor and transferred instantaneously below the robot's tool.

All the data are refreshed by the software every microsecond. This setup thus ensures that the virtual twin mirrors the physical setup accurately.

3.2 PT Following DT

Achieving real-time remote monitoring also requires the Physical Twin to accurately replicate the movements dictated by its Digital Twin. This synchronization ensures that improvements or modifications tested virtually can be applied effectively in the physical environment. This stage is decomposed in several steps.

Step 1: Replicating Realistic Behavior in the Digital Twin. The initial step involves programming the Digital Twin to mimic real-world physics accurately. In this simulation, objects are generated within the boundaries of the conveyor, appearing at random positions and intervals of time (*e.g.* every 7 seconds ± 1 second). When an object is detected by the optical sensor, the conveyor halts, prompting the robot to approach and interact with the object. The robot then activates its gripper, secures the object, and relocates it to a specified slot, mirroring the tasks it would perform in the physical world. In addition, to ensure the same starting conditions, the digital robot is programmed to return to the same default position that its physical counterpart would assume at the start of operations.

Step 2: Transmitting Operational Data to the Physical Twin. The second step focuses on the transmission of operational data from the Digital Twin to the Physical Twin *via* the PLC. This process is crucial for the physical robot to emulate the actions performed by the Digital Twin. Unlike the previous stage, the joints' angles cannot be used in this step as they cannot be modified using the PLC. However, it is possible to solve this issue by using the fact that both twins are programmed to go to the same default position at the beginning of their starts. Indeed, by communicating the tool's displacement vector (with respect to its default position) it is possible for the Physical Twin to move the tool the same way as its digital counterpart (Fig. 4). As the reference conventions differ between Emulate3D and the interface control of the robot, attention has been paid to ensure that the vector communicated is consistent with the conventions used by the UR3e robot. Nevertheless, due to the fact that the robot has been assembled in the same configuration as in the physical world and that a vector is communicated and not the absolute position, no calibration is needed. Indeed, the transformations from one convention to another can be found heuristically. Moreover, the conveyor's state as well as the gripper's state are communicated to the robot.

Step 3: Implementing Adjustments in Real-Time. Finally, the physical system is programmed to adjust its operations based on the input from the Digital Twin. This involves updating the robot's position and the state of the gripper in real-time as per the simulations run on the Digital Twin.

3.3 Towards Real-Time Monitoring

The developments presented so far have established a system where one twin can mirror the actions of the other, controlled by a boolean set at the initialization of the program. This setup is a preliminary stage towards achieving a real-time monitoring system.

The next step is the implementation of a dynamic boolean control for real-time monitoring. The current system's dependence on a static boolean value, checked only during the program launch, limits the flexibility needed for real-time responsiveness. To overcome this limitation, a few changes need to be implemented on the programs architectures to allow the dynamic checking and updating of the boolean. This change will allow changes in the Digital Twin or operator inputs to instantaneously influence the Physical Twin's actions.

A few more changes need to be implemented to reach effective real-time monitoring system. Indeed, at this stage, when the PT is following the DT, the object's position is the one in the virtual realm. Thus, the codes need to be changed slightly so that even when the PT is following the DT the sensor's status is triggered by real events, the object's position is from the physical realm, and the assigned slot of the object too.

This would open the door to real-time operational control by remote operators. In practical terms, this means that an operator could, from a remote location, directly interact with the Digital Twin's interface to initiate changes, which would be immediately reflected in the Physical Twin. For example, if an operational inefficiency or a potential fault is detected, the operator can adjust relevant parameters such as the angles' limits directly in the Digital Twin. This would allow the Physical Twin to still function by imitating its digital counterpart, thus respecting the limitations imposed. In addition this prevent any need for the reprogramming of the robot.

This real-time monitoring and control framework not only allows for immediate operational adjustments but also paves the way for more proactive maintenance strategies. With operators able to monitor and modify the system remotely, potential issues can be addressed before they escalate into critical failures, thus reducing the need for extensive on-site interventions. This proactive approach not only conserves resources but also extends the lifespan and efficiency of the equipment.

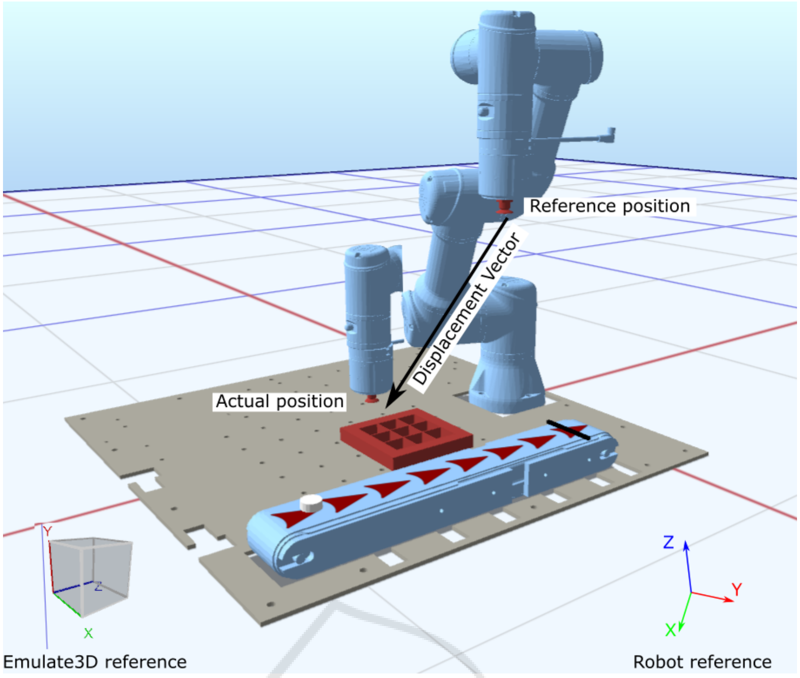

Figure 4: Schematic of the displacement vector illustrating the data transformation and synchronization process between the Digital and Physical Twins. This schematic highlights how displacement vectors are used to ensure that movements are replicated accurately in the physical setup, aligning with the simulations performed in the Digital Twin environment.

4 CONCLUSIONS AND FUTURE WORKS

In this work, the first steps toward real-time remote monitoring of a cyber-physical system are presented. The test case considered is revolving around a UR3e robot which moves objects that are transported to it, and places them in their assigned place. The following results were obtained:

- A Digital Twin of the physical system was built using the software Emulate3D. This virtual model has proven to be an effective replica, accurately mirroring the physical behaviors and operations of the physical robot.
- Robust communication between the Physical Twin and Digital Twin was successfully achieved, enabling data exchange and synchronization between the two twins.
- Depending on the operator's choice, either the Digital Twin imitates the movement and behavior of its physical counterpart, or *vice versa*.

To enable real-time monitoring, the next step is to modify the different programs so that the operator is able — whenever it is needed — to change which twin is following the other on the fly. These modifications should be straightforwards considering the ease of use of the robot and Digital Twin software. Once these modifications implemented, it will be possible, for an operator to remotely take control of the Physical Twin. And then perform the modifications needed on the Digital Twin due, for example, to an incident on the production line. These modifications can then be applied directly by the robot, thus allowing the production line to still run rather than waiting for the on-site intervention.

The developments discussed in this paper open the way for broader implementation and deeper integration of Digital Twin technology in industrial settings, promising significant improvements in system monitoring, maintenance, and management.

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