International Journal on Interactive Design and Manufacturing (IJIDeM)
https://doi.org/10.1007/s12008-024-01969-x

ORIGINAL ARTICLE

A digital twin design and implementation approach for industrial application leveraging programmable logic controllers

Eduardo Zancul[1] · André Oliveira[1] · Yübo Wang[2] · Klaus Schützer[1] · Benjamin Schleich[3]

Received: 5 February 2024 / Accepted: 21 June 2024

Abstract

The Digital Twin allows the merging of the physical and virtual worlds, having many applications in design and manufacturing. While the Digital Twin conceptual foundations are well developed, and fundamental integration technology is available, there is a gap related to generally applicable Digital Twin implementation approaches. Motivated by this, the paper presents a novel Digital Twin design and implementation approach that considers standard industrial automation technologies. The proposed approach relies on a solution architecture positioning Programmable Logic Controllers (PLC) as a central element for Digital Twin deployment for industrial applications. The solution architecture enables a direct connection between the PLC and the Digital Twin platform. The proposal was applied to implement a pneumatic crane for remote operation based on Digital Twin. The assessment demonstrates adequacy in describing implementation activities independently of the specific equipment features, indicating an opportunity for extension to other cases and situations. Thus, the proposed Digital Twin implementation approach can serve as a case reference to support Digital Twin dissemination in practice.

Keywords Digital Twin · Programmable logic controllers · PLC · Industry 4.0 · Remote operation

1 Introduction

Digital Twin is defined as a digital representation of a unique active product or Product-Service System enabled by information and communication technologies [1]. The possibility of mirroring a single physical object with its digital information opens novel opportunities for optimizing product and manufacturing process design and operations [2]. Particularly, Digital Twins enable the operation of Industrial Product-Service Systems [3, 4]. Examples of Digital Twin potential applications in engineering design and manufacturing include real-time monitoring, predictive maintenance, virtual testing, extended simulation, and assembly support [5–8].

The concept of the Digital Twin has been attracting increased interest from scholars and practitioners, reflected in significantly growing research output, especially after 2015 [5, 9–11]. Currently, the conceptual foundations have been defined by previous research efforts [12–14], while the present literature strongly focuses on Digital Twin case applications [5, 11]. Case applications are relevant to prove the concept, integrate related technologies, and test scenarios. However, there are still gaps related to Digital Twin implementation, including effective sensing for physical-virtual data synchronization, the need to promote standardization and scalability, the lack of deployment approaches for existing (legacy) equipment in the industry, and the lack of efficient dissemination approaches for Small and Medium Enterprises (SMEs) that face resource limitations [15, 16]. The current literature regarding general implementation approaches for Digital Twin in industrial settings is still limited.

Motivated by this gap, this paper presents a generic Digital Twin implementation approach that considers standard industrial automation technologies. Therefore, a Design

✉ Eduardo Zancul
ezancul@usp.br

1 Department of Production Engineering, University of São Paulo, Av. Prof. Luciano Gualberto, São Paulo 1380, 05508-010, Brazil

2 Department of Mechanical Engineering, RheinMain University of Applied Sciences, Rüsselsheim, Germany

3 Product Life Cycle Management, Technical University Darmstadt, Darmstadt, Germany

Published online: 06 July 2024

Science Research (DSR) methodology is employed. The research comprehends solution development, demonstration, and evaluation. The proposed approach was applied and assessed in developing a Digital Twin for a system based on a commercially available Programmable Logic Controller (PLC).

The remainder of this paper is structured as follows. Section 2 presents the literature background. Section 3 discusses the research methods. Section 4 details the proposed implementation approach and the related technology architecture and presents the case application and assessment. Section 5 discusses the results and the theoretical and practical implications. Finally, Sect. 6 summarizes the main conclusions and provides recommendations for further research.

2 Literature background

Two research streams are analyzed: Digital Twin implementation approaches and the relationships between Digital Twin and industrial equipment, specifically PLC.

2.1 Twin implementation approaches

The Digital Twin conceptual foundations are currently well-developed in the literature, with several authors providing definitions and perspectives [7, 13, 17]. This paper builds on the definition provided by Stark and Damerau (2019), underscoring that a '*digital twin is a digital representation of an active unique product (real device, object, machine, service, or intangible asset) or unique product-service system (a system consisting of a product and a related service) that comprises its selected characteristics, properties, conditions, and behaviors by means of models, information, and data within a single or even across multiple life cycle phases*' [1]. Conceptually, a Digital Twin entails a comprehensive virtual representation with bidirectional communication with the physical asset. However, some implementations labeled as Digital Twin lack this feature [16]. Such cases are better categorized as Digital Shadows, which refer to a virtual representation based on data at a specific time [18, 19].

Table 1 Selected literature related to Digital Twin implementation

Reference	Main focus and contribution
Stark, Fresemann, and Lindow (2019) [13]	• Digital Twin 8-dimension model. • Digital Twin design elements: (1) Hardware of physical system, (2) Software on Electronic Control Unit (ECU), (3) Data repository, (4) Digital Master and Digital Prototype models, (5) Digital Shadow data, (6) Intelligence/state machine.
Jeong et al. (2022) [20]	• Digital twin technology evolution stages. • Digital twin implementation layers: (1) Digital virtualization, (2) Digital Twin synchronization, (3) Modeling and simulation, (4) Federated Digital Twin, (5) Intelligent Digital Twin services.
Erkoyuncu et al. (2020) [21]	• Digital Twin design framework based on ontologies focusing on equipment adaptability.
VanDerHorn and Mahadevan (2021) [22]	• High-level implementation approach: (1) Outcome Identification, (2) Scope, (3) Virtual representation, (4) Data interconnections.
Singh, Weeber, and Birke (2021) [23]	• Implementation pathway maturity model. • Toolbox focusing on modeling and simulation.

The Digital Twin literature is rich in case applications [5]. Works dedicated to broader, generally applicable implementation approaches to various situations are still scarce in the literature. Nevertheless, related literature explores relevant aspects for Digital Twin deployment. Table 1 presents a summary of selected related works.

The first two studies in Table 1 [13, 20], provide high-level frameworks for Digital Twin understanding, classification, and comparison. These frameworks are also valuable for implementation. The established "Digital Twin 8-dimension model" [13] can support defining characteristics of a forthcoming Digital Twin. The "Digital Twin design elements" [13] and the "Digital twin implementation layers" [20] indicate the needed technical elements for implementation. However, these studies did not intend to provide a procedural implementation approach. Erkoyuncu et al. [21] present a Digital Twin design framework based on ontologies for adaptability and co-evolution with the equipment along the lifecycle. The last two studies in Table 1 [22, 23] indicate recent efforts to detail the Digital Twin implementation as the research and practice in the field advance. However, in one study [22], the results lack specificity to be tested in further research. In the other study [23], there is a specific focus on modeling and simulation, whereas other relevant Digital Twin aspects are not emphasized. The analysis of the extant literature indicates the need to expand the research on Digital Twin implementation pathways.

2.2 Relationship between digital twin and PLC

Programmable Logic Controllers are a central element of industrial equipment operation, providing control and monitoring functionalities. PLCs connect logical commands to the operation of physical manufacturing equipment. Hence, PLC may also play a central role in establishing Digital Twins for industrial manufacturing systems. Notwithstanding, the relationship between PLC and Digital Twin is still underexplored. In this vein, Thürer et al. indicate that '*Programmable Logic Controller (PLC) is an essential part of a digital twin implementation, which receives insufficient research attention*' [24]. Selected literature on the intersection between PLC and Digital Twin is summarized in Table 2.

Thürer et al. aim to propose an architecture for integrating PLC and Digital Twin [24]. As a limitation, the case

Table 2 Selected literature related to Digital Twin implementation

Reference	Main focus and contribution
Thürer, Li, and Qu (2022) [24]	• Propose an architecture for implementation. • Present a Digital Twin prototype for a small lab-scale production environment (based on Arduino).
Ciganek and Zemla (2022) [25]	• Describe a case application for a high bay warehouse on a laboratory scale. • Based on commercially available standard industrial PLC.

application is not entirely based on industrial equipment. Cigánek and Žemla focus on a single case application on a laboratory scale and advance with the use of a virtualized PLC instance [25]. In common, both works emphasize the central role PLC may play in establishing Digital Twin for industrial automation equipment.

3 Methods

A Design Science Research (DSR) methodology is applied to propose and assess a generic Digital Twin implementation approach. A DSR research is appropriate when the research aims to generate new artifacts (e.g., constructs, models, methods, and instantiations) to address a given problem [26].

The DSR methodology adopted in this research has six steps: (1) problem identification, (2) objectives definition, (3) design and development, (4) demonstration, (5) evaluation, and (6) communication [26]. The problem identification and the existing research gap related to Digital Twin implementation approaches are discussed in the introduction (Sect. 1) and further clarified by the literature review (Sect. 2). Based on the current gaps, the research aims to present a generic Digital Twin implementation approach that considers standard industrial automation technologies. The next DSR methodology step – design and development of the proposed solution – is summarized in Sect. 4. After that, a demonstrator was constructed following the proposed approach. The demonstrator was implemented using industry-standard commercially available software and hardware (e.g., PLC SIMATIC S7-1500). The list of materials employed is detailed in Sect. 4. which also discusses the proposal assessment.

4 Digital twin design and implementation approach

A generic Digital Twin implementation approach for industrial equipment based on PLC is proposed (Fig. 1). The process is initiated by conceiving an industrial automation equipment according to existing requirements and related functionalities, resulting in the equipment's conceptual design. Thus, the proposed approach may be employed for various applications.

Next, the conceptual design is detailed in a 3D CAD model and the corresponding Bill of Materials (BOM). This information is central to the following implementation activities organized in physical and digital workstreams. In the physical implementation stream (Fig. 1, lower left side), components are sourced, manufactured, and assembled (including energy and pneumatic supply and cabling). Then, the control program that runs in the PLC is developed and tested. In the digital implementation stream (Fig. 1, lower right side), the CAD model is used to derive a kinematic simulation model. The model is incorporated in the online connectivity platform, which is part of this proposal (detailed in Fig. 2). Afterward, PLC actuators and sensors are mapped to the online connectivity platform, providing the logical linkage of the physical equipment to the functions in the digital platform. This step enables the collection of Digital Shadow data and, later, the remote operation of equipment.

The proposal builds on previous research results. The Digital Twin design elements from Stark et al. [13] are used throughout the process (indicated by numbers 1 to 6 in italics in Fig. 1). The implementation process results in the physical equipment being ready for operation with its corresponding Digital Twin. The implementation approach also comprehends a solution architecture centered on PLC [24, 25]. Figure 2 presents the solution architecture.

The physical equipment is controlled by a PLC through electrical signals. The PLC uses the Open Platform Communications (OPC) protocol to communicate with a computer, which is employed both for programming the PLC and as a gateway between the PLC and the online platform. The platform providing Digital Twin data repository and functionalities is hosted in a cloud server and accessed through a VPN over an Internet connection. The proposed approach and the related solution architecture were applied and assessed in a pilot case.

4.1 Case application context

The case application was conducted within a cooperative research effort between the Fábrica do Futuro Laboratory at the University of São Paulo in Brazil, the Product Life Cycle Management Department at the Technical University Darmstadt and the RheinMain University of Applied Sciences in Germany. Fábrica do Futuro is a Learning Factory focusing on Industry 4.0 technologies. The Product Life Cycle Management Department focuses on the digitalization of products and processes along the product lifecycle. The physical equipment was installed at the University of

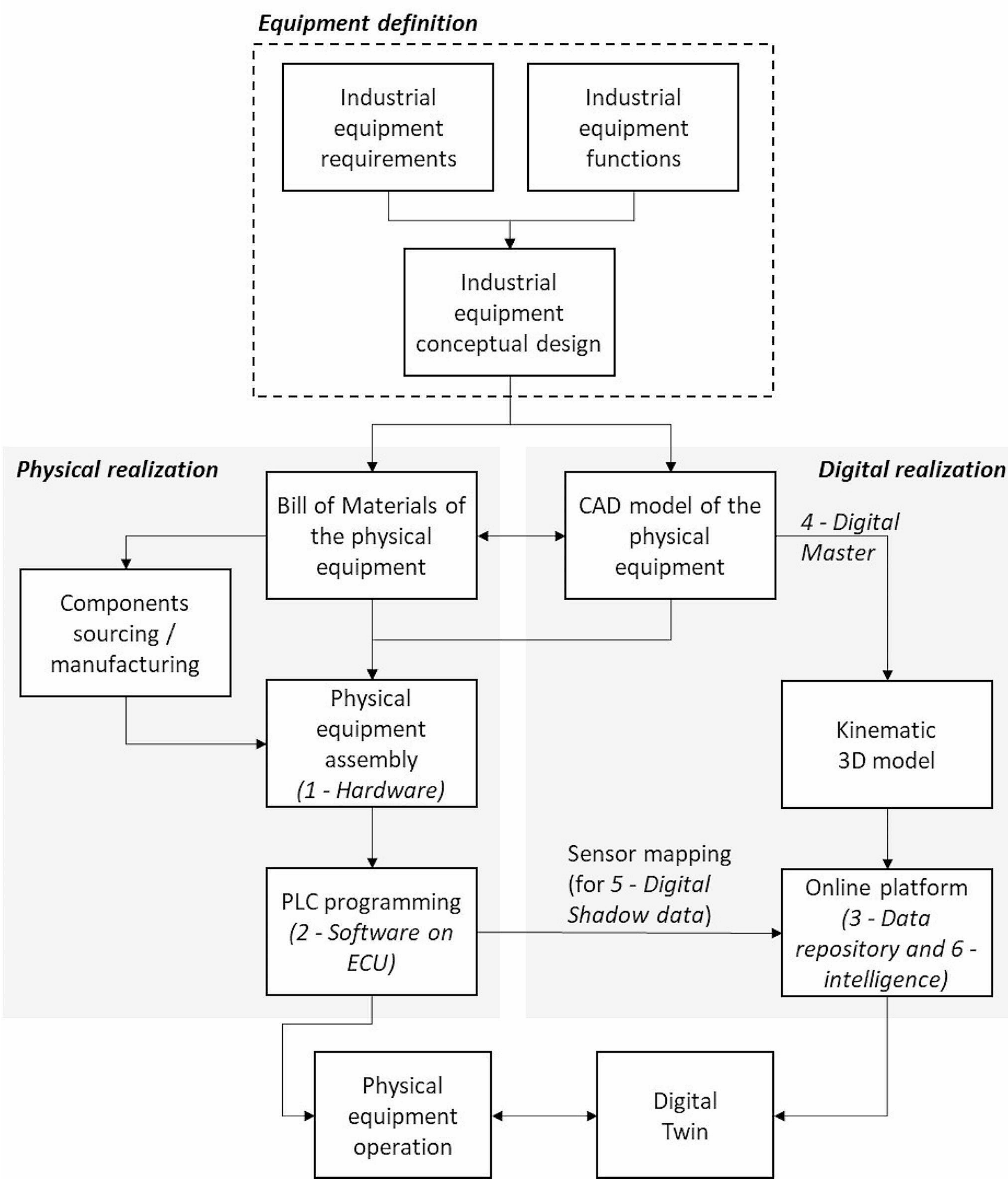

Fig. 1 Digital Twin design and implementation approach

São Paulo, while the Technical University Darmstadt and RheinMain University of Applied Sciences teams coordinated the online platform development. Researchers from the institutions cooperated in integration, implementation, and testing activities.

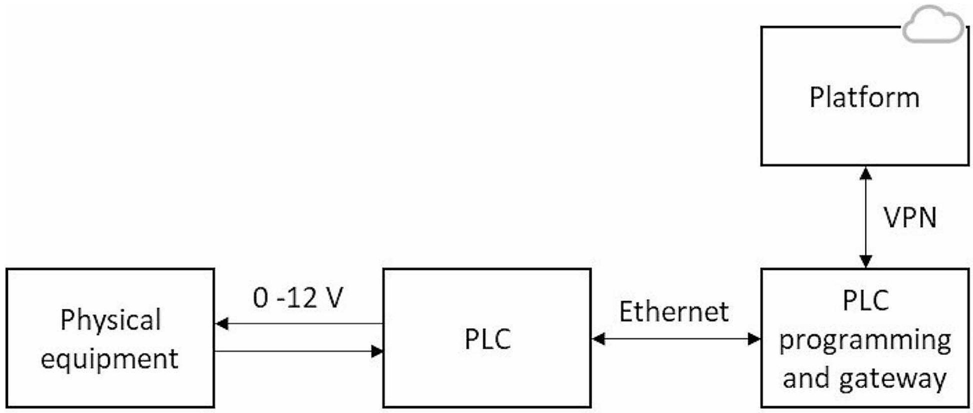

Fig. 2 Solution architecture

4.2 Application and assessment

The proposed approach was applied in developing and implementing a pneumatic crane equipped with a gripper for pick and place with its respective Digital Twin. As a requirement, the solution should be implemented by using industry-standard commercially available software and hardware components. The Digital Twin aimed to support remote operation and state monitoring.

Following the proposed implementation approach (Fig. 1), a conceptual design was established for the crane, resulting in a 3D model (developed using Autodesk Inventor). The BOM included the following materials: 3 air solenoid valves (Festo VUVS-LK20-B52-D-G18-1C1-S), 1 linear actuator (Festo DGC-32), 1 guided actuator (Festo DFM-16-40-P-A-GF), 1 radial gripper (Festo DHRS-25-A) and 5 proximity sensors (Festo SMT-8 M-A-PS-24 V-E-5,0-OE), among other components, cables, connectors, and structural elements. The specified PLC is the SIMATIC S7-1500.

In the physical implementation stream, the needed components were obtained. Two special-purpose structural elements were designed and produced by applying Fused Deposition Modeling (FDM) additive manufacturing process in machines available at Fábrica do Futuro at the University of São Paulo. The crane components were assembled and connected to the compressed air and energy supply. The PLC was connected via an ethernet cable to a desktop computer with the following hardware specifications: Intel Core i5-8500 at 3.00 Ghz, 8GB of RAM, and 1 TB hard drive, running with Windows 11 Pro 64 bit version and featuring Siemens Totally Integrated Automation (TIA) Portal v15, UAExpert and OpenVPN software for programming, testing, and communication purposes, respectively.

In the digital implementation stream, the online platform was pre-configured with the commands to remotely operate the designed equipment and with dashboards to exhibit actual sensors' data obtained from the equipment. A kinematic 3D model was built on Unity with the same restrictions and degrees of freedom as the physical equipment. Following that, the model was uploaded to the platform to behave as a virtual representation of the equipment's actual position. Figure 3 presents the physical system and respective digital representation. In Fig. 3, I1 to I5 represent the sensors: two in the x-axel, two in the y-axel, and one for the gripper position.

To establish communication between the physical and digital worlds, the PLC needed to be integrated into the platform so that data could flow from the equipment to the platform and vice-versa. Therefore, the PLC's IP address and the communication protocol (i.e., OPC UA) were configured in the platform so it could transmit and receive data from the PLC in a secure manner through the VPN. Finally, once the PLC was integrated into the platform, the command buttons, dashboards, and the kinematic 3D model were mapped to the actual nodes in the PLC, thus achieving full interoperability between physical equipment and Digital Twin. Figure 4 describes the implemented solution according to the defined architecture.

4.3 Assessment

Assessment of the remote equipment operation based on Digital Twin was performed with the physical system at the University of São Paulo in Brazil and the online platform hosted in a cloud server (Fig. 5). The solution enabled the remote operation of the equipment with sensors' data feedback to the Digital Twin in the online platform.

The established feedback loop allows the kinematic 3D model on the online platform to represent the system movements according to the actual position indicated by the installed sensors. Additionally, a camera was installed to support the tests with image feedback.

One important aspect of Digital Twin implementation is the latency requirement, which can vary depending on the application scenario [21]. In order to measure the response time of the case application, a test was conducted: sending a command from the platform to the physical equipment

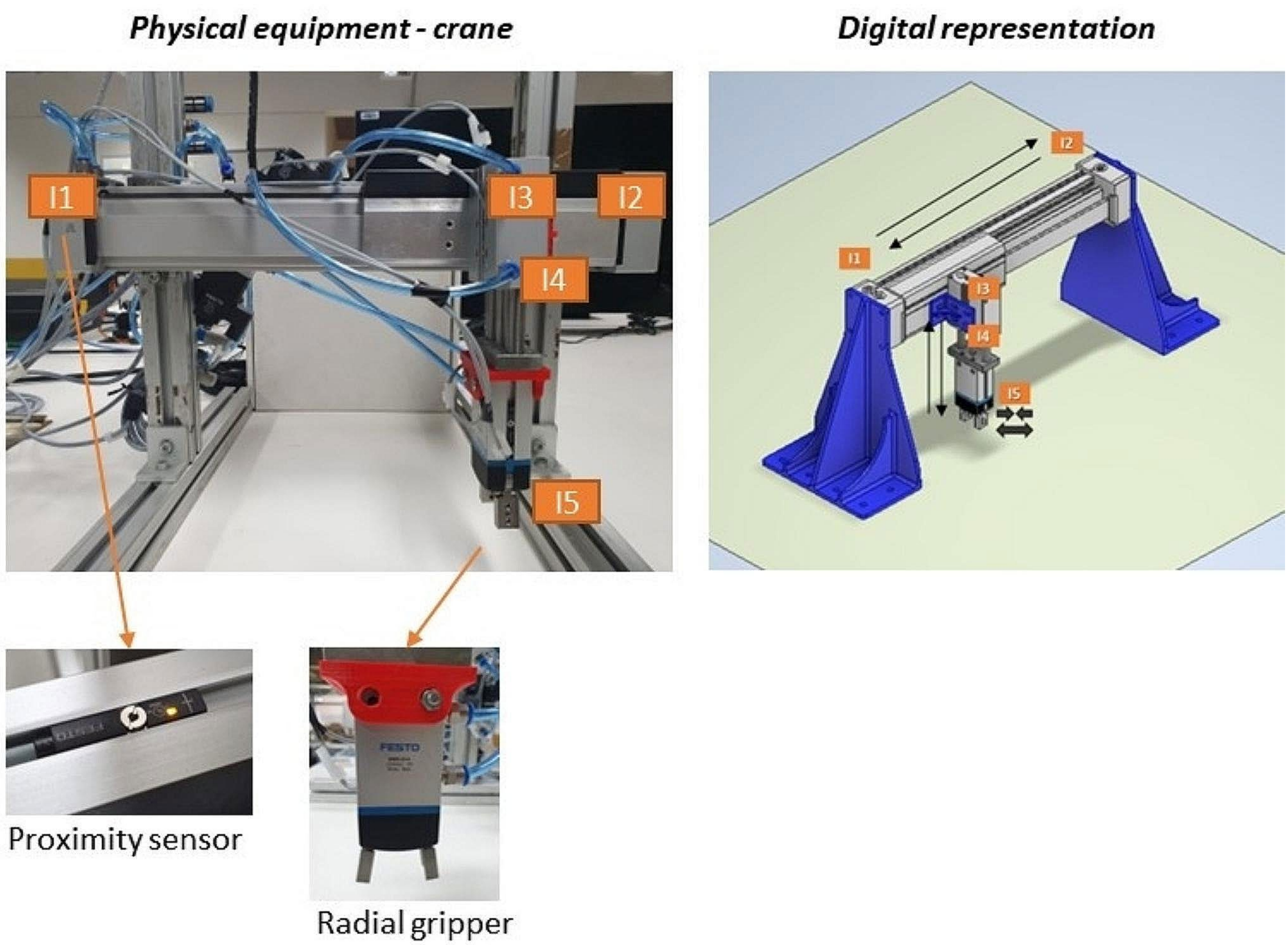

Fig. 3 Physical system and respective digital representation

and measuring the time required for that command to be reflected on the PLC. The experiment was repeated 30 times to mitigate network interference (other VPN performance tests in the literature iterate 10 times [22]). The result was an average delay of 4,87 s (standard deviation of 0,80 s). Although this value can be perceived as elevated, it should be noted that the computer was connected wirelessly to a 50 Mbps link, which can partially account for the results, given that wireless networks are known for high latency [21]. Besides having a wired connection to a faster link, employing data compression techniques to reduce the amount of data transmitted could be a way to reduce latency [23].

5 Discussion

The assessment of the proposed Digital Twin implementation approach indicated strengths and shortcomings. In terms of strengths, the proposed approach demonstrated adequacy in describing the performed implementation activities for an equipment (pneumatic crane) defined independently of the implementation procedure. This indicates an opportunity for future extension to other cases and situations. Moreover, the solution architecture enabled a direct connection between the Digital Twin platform to the PLC. It was also adequate to support remote operation with data feedback to the platform, as demonstrated in Fig. 5.

In terms of shortcomings, the proposed approach mainly focuses on the Digital Twin deployment and basic features. It does not yet address Digital Twin's advanced features (e.g., predictive functionalities and intelligent data-driven services). Moreover, the approach has a procedural nature. It lacks organizational considerations that are needed for technology implementation (e.g., available team knowledge in multiple areas – mechanical design, automation, software development, IT network management).

The proposal contributes to the Digital Twin body of knowledge for the academy and practice. In theoretical terms, it adds to the literature related to Digital Twin implementation [e.g. 13, 21–24] by detailing a procedural

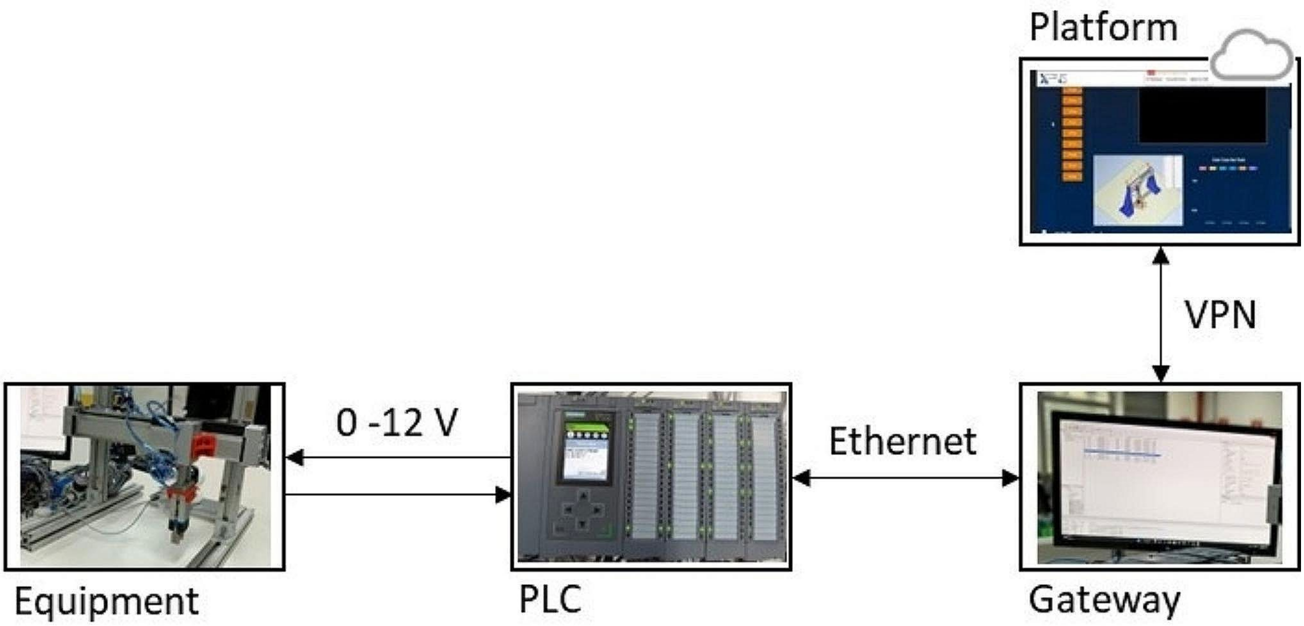

Fig. 4 Implemented solution

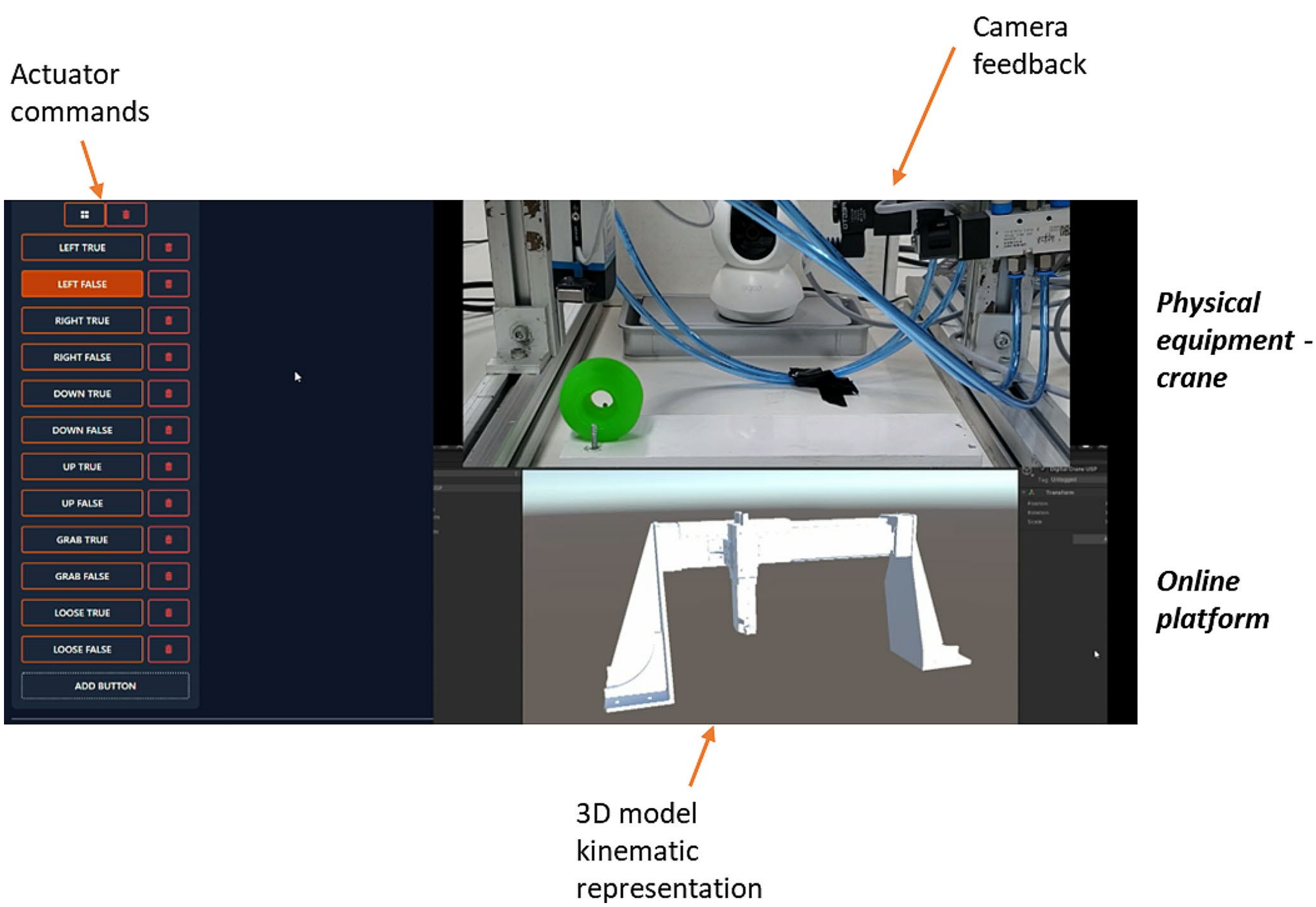

Fig. 5 Test procedure of the physical system and Digital Twin

approach to Digital Twin deployment considering standard commercially available industrial automation technologies. In this quest, the presented results address Zhang et al. (2022) call for works that support Digital Twin application expansion [27] and Kuo et al. (2021) research challenge on the synchronization of physical objects with entities in the virtual space [15]. Moreover, it adds to the literature on the intersection between PLC and Digital Twin [e.g. 25, 26] by providing a novel, feasible solution architecture.

For the industry and practitioners, the proposed Digital Twin implementation approach can serve as a case reference to support Digital Twin dissemination. The proposed approach innovates by describing implementation activities independently of specific equipment features, indicating an opportunity for extension to other cases and situations. As it is grounded on standard automation solutions and knowledge, the proposed approach may be adapted to digitalize existing equipment in the industry and to support SMEs aiming to deploy Digital Twins.

6 Conclusions

This paper presents a novel Digital Twin implementation approach considering standard industrial automation technologies. It also presents a related Digital Twin solution architecture positioning the PLC as a central element. The proposed implementation approach and solution architecture are described in generic terms (independent of a specific case application).

The proposed approach has been applied in developing and implementing a pneumatic crane equipped with a gripper for pick and place with its respective Digital Twin. The implementation occurred in an international research effort involving partner universities in Brazil and Germany. As a result, the Digital Twin enabled the remote operation of the physical equipment with data feedback to the online Digital Twin platform across the globe. The pilot application and testing provided evidence for the assessment of the proposal.

This research has some limitations. First, it was applied in a single case. Although the proposal has generic attributes that aim to support future extensions to various situations, the validity to other cases still needs further investigation. Second, the proposal was assessed with industry-standard commercially available hardware and software, but still in a Learning Factory. Although Learning Factories have characteristics that mimic real production environments, they lack constraints and trade-offs of implementations in manufacturing operations.

This work opens opportunities for future research efforts. The implemented Digital Twin can be used to assess operational parameters in Digital Twin usage, such as data latency in different network configurations (e.g., connectivity based on wireless 5G). Moreover, future research may extend the developed Digital Twin scope to incorporate advanced data-driven functionality and services. Further research may focus on the application of the proposed approach to other cases and situations, including digitalizing existing equipment and in projects directed to SMEs, aiming for generalizability.

Acknowledgements The authors thank A. S. C. for his involvement in equipment conception and 3D modeling and A. M. for supporting the implementation.

Funding This work was supported by the National Council for Scientific and Technological Development (CNPq) under Grant 308804/2020-1.

Declarations

Competing interests The authors report that there are no competing interests to declare.

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