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An Immersive Digital Twin Applied to a Manufacturing Execution System for the Monitoring and Control of Industry 4.0 Processes

Gustavo Caiza [1,2,*] and Ricardo Sanz [1]

1 Departamento de Automática, Universidad Politécnica de Madrid (UPM), 28006 Madrid, Spain
2 Departamento de Electrónica, Universidad Politécnica Salesiana (UPS), Quito 170146, Ecuador
* Correspondence: gcaiza@ups.edu.ec

Abstract: The present research proposes the implementation of an architecture for industrial process monitoring and control for a manufacturing execution system (MES) using an immersive digital twin (DT). For the design of the proposal, cyber–physical systems (CPS), MES, robotics, the Internet of Things, augmented reality, virtual reality, and open platform communication-unified architecture (OPC UA) communication protocols were used to integrate these technologies and enhance the functionalities of the DT by providing greater performance. The proposed work is implemented in an Industry 4.0 laboratory that is composed of Festo Cyber–Physical Factory and CP-Lab stations. The implementation of the architecture is based on ISO 23247, where the following requirements were considered for the design of DTs: (1) observable attributes and 3D design and visualization of all physical production lines in all of their stages, (2) a communication entity through the OPC UA protocol for the collection of state changes of manufacturing elements, (3) a DT entity where digital models are modeled and updated based on the collected data, and (4) user entities through the use of AR and VR to make manufacturing more efficient. The experimental results showed that the architecture enables interoperability between different platforms and control subsystems. It allows for the detection and diagnosis of problems during the execution of the production line; in addition, the high-fidelity simulation and AR and VR environments provided by the DT with data obtained in real time can improve the accuracy and efficiency of manufacturing through a more detailed analysis of the process, providing advantages such as interactive creation for customized products and continuous innovation.

Keywords: digital twin; CPS; MES; Industry 4.0; virtual reality; augmented reality

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1. Introduction

Manufacturing systems are facing a new revolution based on the digitization of assets, processes, and computing capabilities imposed by new data-driven digital architectures. These initiatives emphasize their applications in the manufacturing industry to transform production systems into a new generation of systems that are equipped with CPS characterized by a strong interconnection between the physical and digital worlds. Among all of the enabling technologies of Industry 4.0, the DT is considered to lead the way for cyber–physical integration. With the constant and growing demand for products, several companies have driven forward and adapted to the industrial revolution to face the challenge of decreasing delivery times and having higher quality and product reliability. Therefore, the industry is facing a new revolution, based on the digitization of assets, processes, and computing capabilities imposed by the new data-driven digital architectures [1].

Industry 4.0 drives digital transformation, enabling better operational performance through disruptive technologies such as the Internet of Things (IoT), artificial intelligence (AI), cloud computing (CC), CPS, DT, and big data which have contributed to the rapid development of Industry 4.0 [2,3]. Most initiatives emphasize applications in the manufacturing industry to transform production systems into a new generation of systems that incorporate CPS and are often referred to as cyber–physical production systems. Among all of the enabling technologies of Industry 4.0, the DT is considered to lead the way for cyber–physical integration [4]; this integration is an important prerequisite for smart manufacturing as well as being its core. CPSs and DTs are the preferred means for such integration and have gained considerable attention from academia, industry, and the government. However, there are open points in addressing cyber–physical convergence in traditional manufacturing enterprises to adapt the existing infrastructure to the growing business needs that demand high efficiency and at the same time the reduction of production costs [5]. This drives digital transformation, allowing greater agility and flexibility of production because it can connect the needs of consumers with the industry through automation systems linked to the planning level and enterprise resource planning (ERP) [6]. In addition, thanks to the ability to work with large amounts of data, using sensors and wireless technologies of connected devices in real-time offers promising digitized solutions in various fields of industry, including management, planning, and the control of production [7], allowing manufacturers to save time, increase productivity, reduce waste and costs. This change in the industry involves not only the digitization of processes but also the creation of smart factories, incorporating information and communication technologies (ICT) for the evolution of the supply chain and the production line [8]. However, it should be considered that the development of these systems in the industry involves high costs and requires the change of production systems in several parts of the production line.

CPS are multidimensional and complex systems that integrate the cyber and dynamic physical world by adding new capabilities to physical systems through the integration of machine tools, manufacturing processes, computation, and communication, where processes and operations can be monitored and controlled in these computational spaces [3]. One concept of CPPS is the cyber–physical DT, which is a system that integrates digital models of cyberspace with physical manufacturing processes and resources. It has appeared in recent years with the advancement of new technologies and as sensors and IT infrastructure have become more cost effective and reliable [9]. However, it should be considered that CPS and DTs are not identical from many perspectives, including their origin, development, engineering practices, cyber–physical mapping, and core elements.

The DT represents the interconnection and convergence between a physical entity and its digital representation, and it can exchange information in real-time in both directions; in this way, the digital entity can control the physical entity and vice versa [10]. There are also hybrid DTs that use a combination of physics-based models, artificial intelligence, and data to create a more accurate tool, which could even be simpler to create if the dynamics are unknown [11]. One of the main reasons for using a DT is that manufacturers can observe in real time the manufacturing/logistics environment, allowing for optimization and cost reduction. They have the potential to provide real-time status updates on machine and production line performance; plus, they are useful tools for monitoring and control because they provide a framework to support the high demands currently presented during the industrial revolution. By using a DT, mechanical damage during implementation or late detection of the problem in the early stages of the project can be avoided [12].

The contribution of the present work is the implementation of an architecture for the monitoring and control of industrial processes based on an immersive MES and DT system. For the design of the architecture, CPS, MES, robotics, IoT, AR, VR, and industrial communication protocols in OPC UA technologies will be used. To integrate these technologies and enhance the functionalities of the DT, providing greater benefits for users and customers, the proposal will be subsequently validated through experimental tests in the Industry 4.0 laboratory to verify the correct operation and show the advantages and challenges presented by the immersive DT in a continuous production line.

2. Related Works

This section provides a general description of works carried out by other authors to establish the proposed architectures and the technologies and protocols used for the implementation in the industrial sector. For the selection of the articles, the following aspects were considered: (1) methodologies proposed for the implementation of DTs in the industrial area in the last 5 years and (2) combinations in groups of 2 and 3 of the following keywords: [Digital Twin, Industry 4.0, Virtual Reality], [Digital Twin, Industry 4.0, Augmented Reality], [Digital Twin, OPC UA], and [Digital Twin, CPS, MES]. After selection, 18 articles implemented in the industrial field and using any of the technologies or industrial protocols described in the first paragraph were obtained. It was observed that in the collected works the implementations are not governed by a standard for the design of the DT architecture. Also, three papers were selected at the simulation level because, in the proposal, they used industrial protocols with MES and CPS for their proposals which served as a guide for the union of these technologies. The review will be organized according to the methodological approach, technologies used, and applications to analyze the benefits and challenges of developing such technology.

This review aims to conduct a synthesis and critical analysis identifying the strengths and limitations of the proposals made by other authors, in addition to identifying current trends, developments, and rapid evolution. In this way, the architectures and technologies used are considered in this research according to the results obtained when applying them to industrial processes.

In the first part, articles were selected that showed DT proposals that were implemented in the industry as described below. The authors of [13] present an architecture to perform an adaptive DT; the objective was to show that online optimization and adaptivity can be performed using an early simulation. Within the proposal, there are constrained, dynamic, and autonomous subcomponents that must be considered to associate with any of the state, design, and configuration components and system behavior. The system is implemented in a shoe production process where the results showed that the proposed architecture is suitable for production environments that undergo constant and unpredictable change, whereby obtaining synchronous and asynchronous data obtained from the physical system serves as a basis for such interaction and obtained a continuous production of customized shoes and can continuously reconfigure the design to adapt to new user needs. In [14], they propose a DT to predict the behavior of products in the first phase of manufacturing by creating a set of DT modules that can be reused and recomposed to create variants of DTs. The case study is performed for two cases, the first one a need of a manufacturer and the second one an industrial case of propulsion systems. In both cases, the results showed how the modular platform design has an impact on the cost of physical and digital definition, if commonality and reusability aspects are considered, in addition to improving the cost effectiveness of applying a modular approach to the creation of DTs. In [15] they propose the integration of a digital shadow (DS) simulation model with an MES, thus creating a DT that has two frameworks, one for error state management and the other for triggering disassembly processes; the system was implemented with the Industry 4.0 Lab MES, Matlab 2023 software was used to perform the simulation environment and the sensor data were sent via an OPC UA protocol and then communicate with the MES via TCP/IP. The results showed that by adding a DS to the MES, the system becomes a DT with bidirectional communication and with the possibility of monitoring and decision-making. In [16], they produce a DT with object detection using deep learning (ML). The DT was carried out in Siemens NX and an S7 1200 programmable logic controller (PLC) (Simatic S7-1200, manufactured by Siemens AG in Mexico) was used, which through the OPC-UA protocol communicated the physical and virtual environments; for the ML YOLOV3, the results showed the feasibility of implementing this type of system with ML with an average of 1.083 s to a total signal travel time of 1.338 s. In [17], they propose a DT lifecycle model with methodologies and tools for management using Industry 4.0 concepts, such as the asset management shell (AAS), international data spaces (IDS), and standards such as OPC–

UA and AutomationML (AML). For the case study, a sorting station that has industrial sensors and actuators was used and the results showed that it is a generic and flexible architecture based on existing DT frameworks, and since they are open architectures for smart manufacturing, they are key to solving problems of interoperability. In [18], they developed a DT that has integrated visualization technologies and the simulation of process parameters. The implementation is carried out in a typical machining process, which has an S7-1200 PLC and bidirectional communication based on the TCP/IP protocol, with the simulation module based on finite element modeling (FEM), which was implemented in ANSYS, and the virtual model was developed in Unity. The results showed that the system facilitated the visual representation of microstructural data variations by obtaining and displaying FEM simulated results of real-time stress variations of the workpiece, and these data can be used for real-time control and optimization; in addition, it significantly reduces trial and error costs, minimizing processing errors and facilitating the comprehensive management and optimization of processes.

In [19], they present an architecture that allows for data exchange between remote simulation and the physical twin; the architecture has the following layers: local data, an IoT gateway, cloud databases, and a layer that contains emulations and simulations. This architecture provides a real-time, service-based infrastructure for vertical and horizontal integration and can be deployed in new and legacy production facilities. The implementation was performed on a robotic gripper that has known failure modes; therefore, the ability of a DT to detect anomalies in the functioning of the physical twin will be evaluated. The results showed that by creating six layers, the functions of the proposed architecture can be distributed; however, it must be considered that the latency increases. In [20], involving a general cloud-based DT framework to support smart manufacturing services, this proposal presents the integration of modularized cloud intelligence, modeling, and visualization to achieve improved remote accessibility and will be implemented for a manufacturing system for robotic assembly. An RPI card is used to acquire data from the physical process and, using the message queuing telemetry transport (MQTT) protocol, it sends the data to the cloud for the creation of I4.0 services. The results show that the proposal enriches the path to realize cloud-based DT and features cloud intelligence, DT modeling, and web-based DT visualization, providing a feasible solution to upgrade a legacy manufacturing system to a digitalized and intelligent system. In [21], they propose an architecture using a finite state machine (FSM) to guarantee the functionality of the associated control systems which can be integrated and used for the simulation requirements of a production process. The implementation is carried out through IoT and OPC UA communication integrated into the industrial materials classification production line. The results showed that the proposed solution is suitable for the implementation and design of a physical device and allows the proposed method to be verified before the final implementation; in addition, it presents a flexible design, which ensures the agile development of various parts of the system and the development of individual tasks in parallel. In [22], they propose an architecture to merge SCADA systems with a DT with an architecture based on OPC UA with Ignition software and by adding an RPI card. The proposed architecture consists of a server, gateway, cloud service, and end-user nodes. The results showed that the architecture simplifies system connectivity and reduces the computation cost of process controllers by utilizing a gateway device to perform more demanding processing tasks. In [23], they present the integration of a DT in a production workshop that has Industry 4.0 technology, where it was considered to perform precise digital mapping with multidimensional, static, and multidimensional characteristics that describe the perspectives of geometry, physics, behavior, and rules. Production data, equipment operation data, production process parameters, and operation parameters were considered. The results showed that the proposed system provides an implementation method and approach for collaborative interaction and iterative operation problems caused by complex coupling in the process industry. In [24], they propose an online modeling and control method for complex assembly processes based on a DT in conjunction with a particle swarm optimization algorithm to dynamically adjust the process parameters. The framework consists of three layers: a physical layer, a DT layer, and an optimal control layer. The physical layer consists of industrial robots, operators, and assembly parts. The DT layer provides high-fidelity, multi-physics, multi-scale simulation and prediction capability, and finally, the optimal control layer perceives and analyzes the real-time state of the assembly process through DT models in the DT layer to obtain the optimal parameters. considering the precision and efficiency of the assembly. The results show the superiority of the proposed approach compared to the traditional method because it significantly reduces the iteration time and improves the assembly quality. In [10], they propose a DT focused on self-development, and it will be implemented in an existing production system to develop data following the concept of Industry 4.0. In this way, the cost of starting a very low structure without automation is taken advantage of and the results are obtained in the form of data to analyze it to adapt it with automatic layering systems with maximum efficiency. The design was made based on the automation pyramid for data collection and sending them to the computer and HMI to be shown to the operator. These data are stored in MYSQL the Modbus TCP/IP protocol was used for communication, and through OPC, the data were sent to LabVIEW for real-time monitoring and communication with the HMI. In [25], they realize a DT-based distributed manufacturing system for Industry 4.0 with on-the-fly replanning capabilities powered by AI with the objective of autonomously verifying, interpreting, and executing production plans. The proposed methodology executes the initial plan while the AI searches for more efficient alternatives and sends better solutions to the MES, which updates the new plan during production. The results are shown and validated in a use case using an Industry 4.0 testbed, which is equipped with an automated transport system, renewable energy sources, and KUKA industrial robots. The results showed that it is feasible to encapsulate the digital twin (basic digital twin based on the PDDL model) with a scheduler into a new enhanced digital twin (digital twin with AI scheduler), combining the advantage of rescheduling capabilities with a distributed MES.

Subsequently, studies that implement DTs in conjunction with AR or VR applied in the industry were reviewed to establish the architectures and technologies used by the authors in [26], who propose an AR-based DT method for the compatibility verification of building information modeling (BIM) data applied in semiconductor manufacturing (FAB). The system was implemented in Unity-based AR/visual SLAM along with AR Foundation using SLAM, 2D tracking, and local anchoring API in ARCore. The results showed that the implemented system allows for precise adjustment of the AR model and the real object through AR tracking and anchoring technology, improving the compatibility of objects. In [27], they develop DT in industrial environments, with AR and VR emphasizing the incorporation of other technologies such as system integration, connectivity with industrial protocols, and cloud services to enhance the capabilities of the digital environment. They use the Unity platform as a real-time 3D development tool due to its cross-platform capacity, and for system integration, they use Node-RED and the MQTT protocol. The results showed that the proposed DT provides a more complete understanding of the modeled process, with real-time interaction and dynamic visualization allowing for improved decision-making. In [28], they implemented a DT for the control and monitoring of a process with AR; the system was implemented in a modular production station MPS 500. The architecture consists of a PLC and a Raspberry Pi for sending process data to the cloud using Modbus TCP/IP and the M2M protocol; subsequently, the data are sent from the RPI to Unity for the development of the DT application for visualization and control via AR. The results showed that robust industrial protocols can be used for communication in interaction with AR, in addition to producing a DT with a user-friendly interface. In [29], they present the design and implementation of an AR-based assembly line for Industry 4.0 applications. For the design, they used Unity to create an interactive and easy-to-use AR application for training, and it was implemented in Festo's MPS-PA. Among the technologies that stand out is computer vision, and a scanner was used to produce a 3D design, and it was later exported to Solid Works. The results highlighted the potential of AR technology for assembly line operations, improving assembly line operations, productivity, and training.

Finally, works were reviewed at the simulation level where the results obtained show the feasibility of improving the processes and can also be implemented in the industry. In [30], they propose an architecture to promote a reconfigurable manufacturing system (RMS) through a DT, where it is proposed to create an integrated platform for simulation and monitoring. In addition, they analyze how the CPS-MES architecture serves the evolution of the RMS; to validate the proposal, they implement it in Unreal Engine 4 (UE4) software where the simulation of planned RMS configurations is carried out; the performance of the configurations is calculated planned, and they obtained the optimized configuration. In [31], they analyze the asset administration shell (AAS) in terms of structure, components, sub-models, and communication protocols, such as OPC UA and MQTT, or interfaces that allow vertical and horizontal communication. The virtual production test bench and its implementation are carried out at the simulation level by creating a virtual factory where the tests are carried out, and it was observed that it considerably reduces time and uses relevant standards defined by the user, such as the names and attributes of the parameters. In [32], they propose the realization of a DT based on the DT definition language for data exchange with any application that complies with the open platform unified communications architecture; they use OPC UA to structure in DT definition language (DTDL). The implementation of the model was carried out at the simulation level.

The literature reviewed shows several trends; first, we will highlight the limitations and challenges encountered, where it was observed that most of the works presented are not governed or based on a standard for the design of the DT architecture; with it being a form of technology that is under development, there are open proposals for both the design of digital entities, communication, and the data collection of physical environments. It was also observed that the proposals do not include an analysis of security, latency, and resource consumption, which are important factors in the industry. However, being a developing technology, the "ISO 23247" standard [33] in force for the development of DTs in the industry does not present restrictions regarding the use of technology, platforms, and communication protocols used for their implementation.

It was observed that the most used protocols for communication are OPC UA, TCP/IP, and MQTT, which allow bidirectional communication and can be used at different levels of the automation pyramid, allowing for horizontal and vertical integration according to the required need in the processes. On the other hand, several trends and enabling technologies for the development of this technology and the interoperability that can be achieved between different platforms to design DTs are evidenced. Table 1 shows the nine papers that are considered relevant for this research because the proposed architectures used for industrial protocols for bidirectional communication were implemented in industrial case studies and show the process for the integration of said technologies and protocols.

Table 1. List of the most relevant papers with architectures implemented in the industry.

Ref	Paper	Protocols	Implementation
(Negri et al.) [15]	MES-integrated digital twin frameworks	OPC UA and TCP/IP	Industry 4.0 Lab
(Gichane et al.) [16]	Digital Triplet Approach for Real-Time Monitoring and Control of an Elevator Security System	OPC UA	Elevator
(Stojanovic et al.) [17]	Methodology and Tools for Digital Twin Management—The FA3ST Approach	OPC-UA and AML	Classification station

Table 1. *Cont.*

Ref	Paper	Protocols	Implementation
(Wang and Yang) [18]	A Digital Twin Platform Integrating Process Parameter Simulation Solution for Intelligent Manufacturing	TCP/IP	Machining process
(Kruger) [19]	A six-layer architecture for the digital twin: a manufacturing case study implementation	OPC UA	Robotic gripper
(Strelec et al.) [21]	IIoT Device Prototype Design Using State Machine According to OPC UA	OPC UA and MQTT	Production of industrial materials
(Abdelsattar et al.) [22]	An OPC UA Client/Gateway-Based Digital Twin Architecture of a SCADA System with Embedded System Connections	OPC UA	Laboratory MPS 500
(González-Herbón et al.) [27]	An Approach to Develop Digital Twins in Industry	Node-RED, MQTT, and Modbus	Robotic cell
(Caiza and Sanz) [28]	Digital Twin to Control and Monitor an Industrial Cyber-Physical Environment Supported by Augmented Reality	Ethernet and M2M	Classification station MPS-500

It is also evident that the use of AR and VR increases the capabilities of the DT in the industry. Among the main advantages is the interaction and experience that AR provides to the user, while VR allows for more realistic simulation environments based on the data acquired from the process in real time. Among the types of software used, Unity provides several advantages to implement the DT, and the communication protocol used is MQTT due to its ease and performance; in addition, there is Node-RED, which is an open-source development tool based on programming.

Finally, from the works reviewed at the simulation level, we can highlight mainly the proposal of integrated platforms for monitoring and simulation with the use of industrial protocols. The proposed DT systems show that the main advantages of using DTs in the processes can be applied to the field, control, and management levels. The results show a considerable time reduction in the processes and optimization in the processes by being able to perform an early simulation with real data.

In the present research, the implementation of an architecture for an immersive digital twin in an MES under the ISO 23247 standard will be carried out. It will be supported with AR, VR, IoT, CPS, and OPC UA protocol technologies. It is hypothesized that the proposed architecture will allow for the integration of these technologies to increase the capabilities of the DT, providing greater benefits to users through a friendly and flexible interaction between physical and virtual entities, with the aim of improving the efficiency of processes and decision-making in real time.

3. Methodology

To establish the architecture of the immersive DT in an Industry 4.0 environment for process monitoring and control at both plant and management levels, the present work is based on the ISO 23247 standard, which was published in 2021 by the ISO TC 184/SC 4 committee to standardize an architecture framework to support the creation of DTs for manufacturing applications. It should be considered that the type of manufacturing supported by ISO 23247 depends on the standards and technologies available to model the observable manufacturing elements. Therefore, it provides an open framework to use different technologies where different domains can be used for the data, i.e., the standard does not prescribe specific data formats or communication protocols. The framework guides the development of a DT and is composed of four application layers [33].

ISO 23247-1: Principles, concepts, limitations, and general requirements for the development of digital twins in manufacturing.

ISO 23247-2: Model architecture with reference functional views based on domains and entities.

ISO 23247-3: List of basic information attributes for observable manufacturing elements.

ISO 23247-4: Technical requirements for information exchange and protocols between entities within the reference architecture.

The proposed work implements an architecture of an immersive DT of the industry 4.0 laboratory that is composed of the Festo Cyber–Physical Factory (CPF) and CP-Lab stations, which allows for the monitoring and control of the processes in addition to schedule orders and specifying the configuration of the product from the digital environment. The complete cell phone assembly process must be carried out in the two stations where in the CP LAB, the assembly of the bottom part of the phone is carried out, the plate is added, the elements are added according to the order, quality control takes place through artificial vision, and finally, there is the inventory. In the CP Lab, meanwhile, the top cover is placed, sealed using pressure, and classified according to the user's request. For the implementation of the proposed architecture and to be based on the ISO 23247 protocol and its layers, the following structure will be followed: (1) realization of the 3D design and visualization of all physical production lines in all of their stages and of the available resources in the cyberspace model, (2) establishment of bidirectional communication with the existing manufacturing system through protocols such as Node network and OPC UA, (3) communication of the physical and virtual environments for obtaining real-time data from all stages of the process and thus establishing monitoring and parameter settings from the physical or virtual environments, and (4) performing simulation, configuration and optimization experiments with the DT in the CP lab and CP Factory from the physical and virtual environments.

The proposed architecture of the immersive DT will be implemented in the Industry 4.0 laboratory to extend its functionalities, data, and bidirectional communication. The wireless data will be collected throughout the production cycle to allow for history, simulation, and data analyses for optimized decision-making and thus increase the advantages of the current MES implemented in the laboratory. Within the hardware and software used in the architecture, the following are used: (1) Industry 4.0 Lab, (2) TIA Portal software for PLC programming and configuration, (3) Blender and Solid Works for the design of the 3D virtual environment, (4) Unity which allows for the development of AR and VR applications and is compatible with multiple platforms such as Linux, Android, Windows, IoS, and Android, and (5) the OPC UA protocol that enables bidirectional communication based on client/server and publish/subscribe communication models and provides a semantically enriched information model to represent data. The steps for the proposed architecture are described in detail below.

3.1. Digital Twin Implementation

The Industry 4.0 Lab is a modular, flexible, and open training system that allows for the improvement of cooperation and skills in different areas due to its network, communication, and data acquisition systems. It consists of the following modules: CP Lab Conveyor, CP Factory basic module Branch, CP factory AS/RS for pallets, CP factory robot assembly with artificial vision, CP application camera inspection, and a Movil robot for workpiece carriers. The stations are equipped with the PLC "CPU 1512SP-1 PN for SIMATIC ET 200SP based on S7-1500 CPU 1513-1 PN" which is a PLC with medium requirements in terms of program volume and processing speed, for distributed configurations via PROFINET

IO or PROFIBUS DP, as well as PG/OP communication, open IE communication (TCP, ISO-on-TCP and UDP), web server and S7 communication (with loadable FB), and OPC UA (Client/Server). For the proposed architecture, the MES implemented in the laboratory is used via the OPC UA protocol as a server for the bidirectional communication for the proposed DT and with Node-RED as the OPC UA client for sending data to the cloud and subsequent communication with AR and VR as shown in Figure 1.

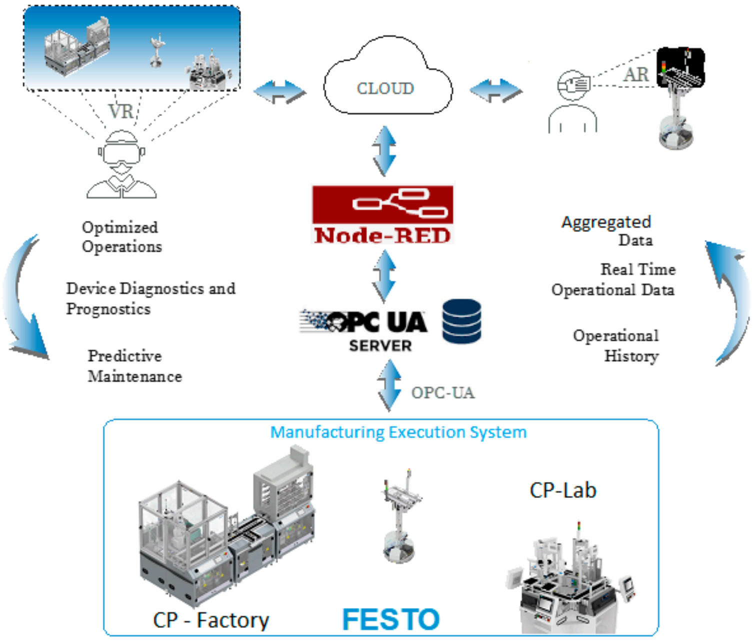


Figure 1. Immersive DT architecture for the MES.

To implement the communication of the proposed architecture, the platforms shown in the class diagram in Figure 2 will be used, where the process data are sent through the OPC UA and Node-RED protocol to the cloud and then these data will be displayed on the PC screen and will also be used to create monitoring and control applications in virtual and augmented reality environments. The packages and libraries used for the bidirectional communication in each of the stages are also detailed; in later sections, each of these stages are explained in more detail.

The programming and configuration of the stations were performed using TIA Portal software where it should be considered that there is a large data volume in the stations; therefore, within the programming, the main blocks to be used are: organization blocks (OB), which is used to control the flow of the program because they allow for processing cyclically and also allow for data communication between different levels defining the behavior of the system; in the proposed DT architecture, they are used for the start, end, and synchronization events of the models. Function blocks (FB) are a reusable block that allows the storage of data permanently to perform a specific task; these data are available at any time or stage in the proposed architecture and are used to represent different components (sensors, actuators, etc.) of the DT, giving greater flexibility when simulating the behavior of that component. Data blocks (DB) store important data for the operation of the process, in the presented framework they are used to store the real-time information of the DT components. In addition, these blocks are used to send the information to the Node network for further processing and visualization. Function blocks (FC) are used to perform complex calculations and additional operations required by the DT to make decisions based on data and process states. The network topology was configured using TIA Portal where the stations communicate through the profinet protocol and then, these data are sent through the OPC UA and Node network to interact with the DT. Figure 3 shows the topology of the devices and networks used in the proposed architecture.

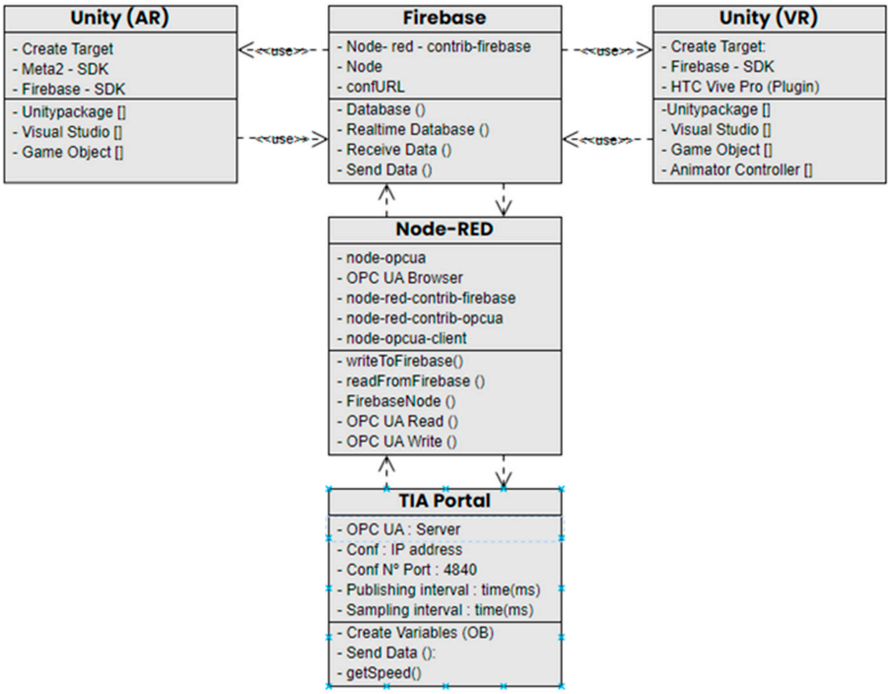


Figure 2. Communication class diagram for the proposed architecture.

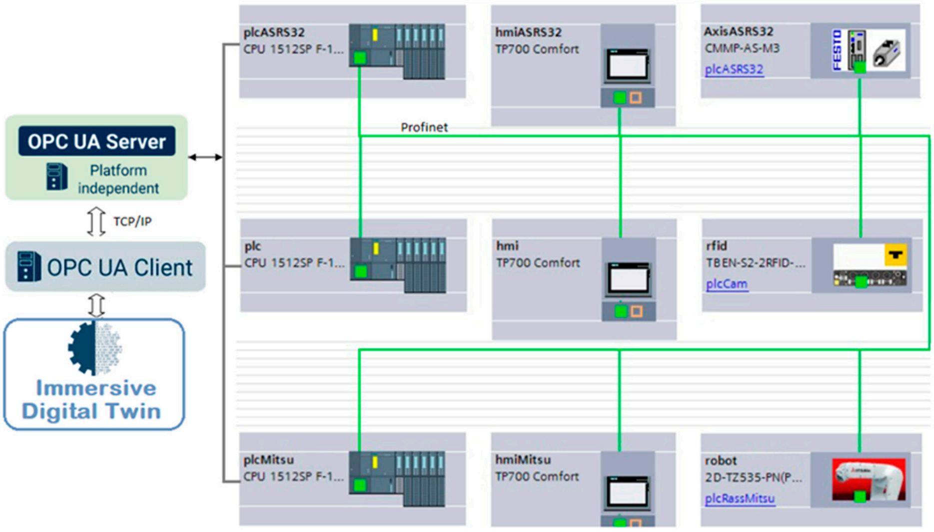


Figure 3. Device and network topology of the DT.

3.2. Development of the Digital Environment

The creation of the digital environment was based on the ISO 23247-3 standard and was performed in the Blender and Solid Works environment, which is a type of software used for modeling and creating 3D content, in addition to having the option of rendering, modeling, and animation, making it perfect for interaction with AR and VR, allowing for the creation of 3D models to map the physical and kinematic properties of the elements and devices of the plant, and subsequently, with the Unity engine, they are exported to create animations in real-time. They also have high performance and enough libraries and communication protocols to interact with different devices and subsequently define the coupling of movement depending on the processes. The simulation module was developed as a virtual model, which is a representation of the production lines and physical resources, which are connected and synchronized with the physical entity in real time through data received from wireless sensors and simulation data. Figure 4 shows the sequence to carry out the digital design of the stations, which is carried out through the following process: (1) add the required station models to Ciros Studio V 6.2, (2) export the environments with the extension STP to Solid Works, (3) export the files in STL format files to Blender where the editing for the simulation is performed and the elements are increased according to each station to achieve a more faithful finish of the physical design, and (4) the digital model file is integrated into Unity, with the programming that will allow for the establishment of bidirectional communication and synchronization between the physical twin and the DT.

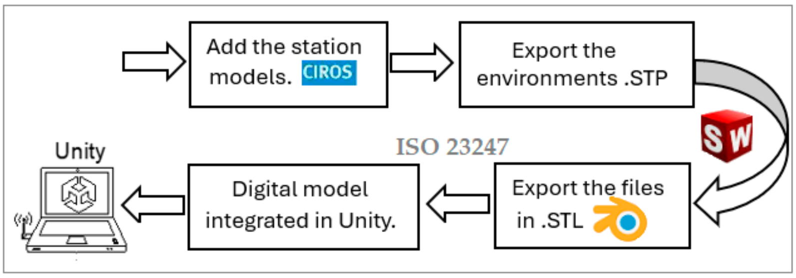


Figure 4. Device and network topology of the DT.

3.3. OPC UA Communication

The configuration of the OPC UA protocol is carried out using TIA Portal software where the following steps are performed: OPC UA server activation, IP configuration, communication port configuration, DB block creation, OPC UA server interface creation, sampling, publication times configuration, and finally, security configuration.

It should be considered that the DB blocks are used to store the information of the DT components, so all of the variables to be used in the DT should be created and one should make sure to activate the accessibility to them to guarantee the communication between the different environments. In addition, when selecting the server interface, the variables to be transferred to the client must be selected and an ID node will be observed for each enabled variable; these variables will be used for communication from Node-RED. Figure 5 shows the OPC UA communication diagram used in the proposed DT architecture.

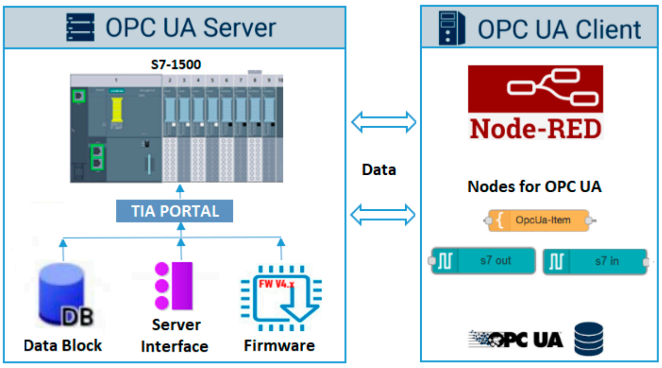


Figure 5. OPC UA communication diagram with Node-RED.

The OPC UA protocol is used because it allows for bidirectional communication between different platforms and levels of the automation pyramid, in addition to communicating with devices from different manufacturers. The client–server architecture is used because it is compatible with the OPC UA communication framework and implements a security layer with authentication, authorization, encryption, and data integrity. As field devices become more powerful in terms of CPU and memory performance, there is a trend to incorporate OPC UA server functionality within field devices to provide direct data access to external OPC UA clients [34].

3.4. PLC Communication with the Node Network

The programming and configuration of the PLC were carried out using TIA Portal software where the programming of the entire process is carried out for each of the stations. The PLC used is the S7-1500 where the input and output modules used in the process are configured. Through Node-Red, one can interact with the information from the PLC and in this way obtain real-time data from the DT with bidirectional communication for monitoring and configuring the process. For communication between the PLC and Node-Red, the TCP/IP, MQTT, OPC UA, etc., protocols can be used. The proposed architecture is shown in Figure 5 where OPC UA is used and the PLC is configured to act as an OPC UA server, and the nodes and TAGs that will be sent to Node-Red are also defined. In Node-Red, the nodes are installed for communication with the OPC UA protocol. In our case, "node-opcua" and "OPC UA Browser" were used. Subsequently, the connection is established by configuring the IP, cycle time, specific port, slot, and rack; these parameters are established to have an ordered identification of the variables received in node-red. The PLC TAGs must be translated into the format required by the new instances, and specific URL addresses can be used for each interaction. Subsequently, each OPC UA node belongs to a class called NodeClass where the common attributes of the OPC UA nodes are defined as shown in Figure 6.

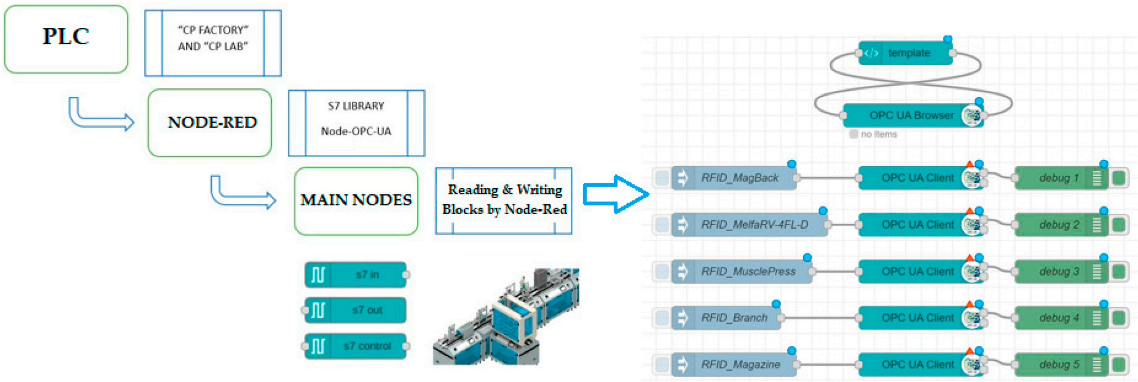


Figure 6. Process communication with OPC UA and Node-RED.

Once one has the information in Node-Red, the data are sent to the Firebase cloud. In the cloud, a project name and location are configured, and the database and security that will also be used are configured. While in Node-Red, the configuration is carried out to send the data obtained from the process to Firebase; first, the cloud libraries used, in this case "node-red-contrib-firebase", must be installed and then, the configuration is carried out of the Firebase nodes where data writing and reading operations are established.

Once the sensor data are in the Firebase cloud, the configuration is processed with Unity to create the DT applications with AR and VR. First, the Firebase SDK is installed in Unity software, which allows for communication between the platforms, and then, communication is carried out using the TAGS used in the programming to link with the virtual environments that were previously designed to make the animations based on of the process and data obtained. Finally, the sending of data from Unity to Firebase is configured to provide feedback and control the process from both physical and virtual environments in real time.

4. Results

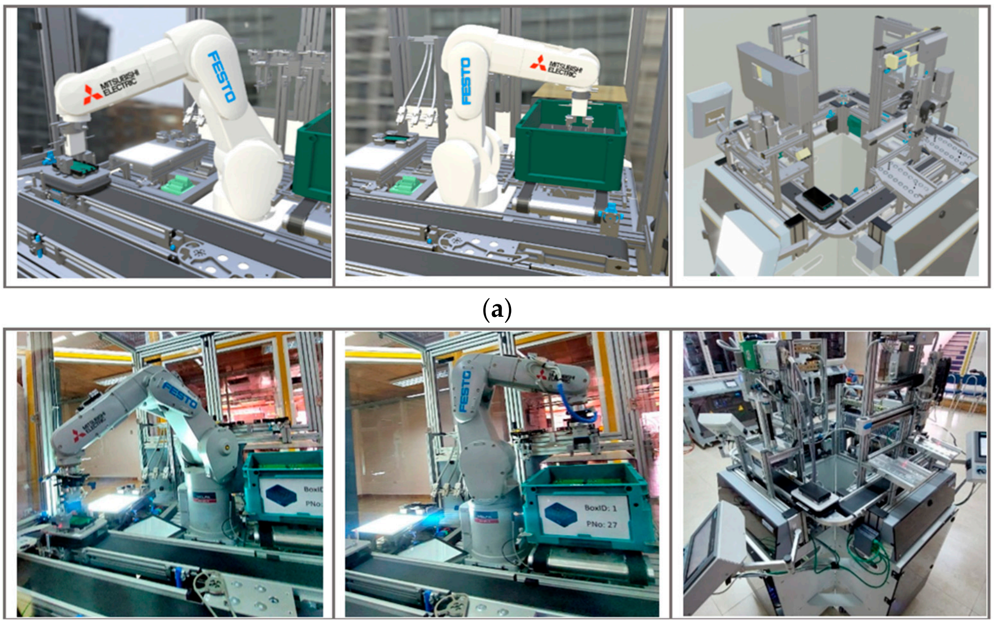
To validate the results, 3 approaches will be used. The first consists of implementing a continuous production flow and subsequently generating internal and expert errors controlled and caused by an operator to compare the response times of the system with the conventional MES vs. the system with the DT-MES. The second validation tests the AR and VR environments with the DT and an interaction is carried out with all of the elements of the manufacturing cell for the supervision, simulation, and control of certain parameters. In the third validation, the transportation times between the stations are measured, for which several obstacles will be placed between the stations and the mobile robot will have to trace the most optimal route obtained with the simulation models and will measure the times in the traditional system and the proposed system.

4.1. Conventional MES vs. the System with the DT-MES

To analyze the results of the proposed architecture, the generation of errors in the process was carried out where error states occurred in different scenarios in the production cycle of the MES.

1. Twenty orders are made from the conventional MES with different characteristics, and during execution, three errors are generated: (1) turning the plate, (2) changing the transport carriage, and (3) removing a fuse from the assembled plate.
2. Subsequently, the same number of orders, characteristics, and the same errors are generated as in the conventional system; however, the system works with the proposed DT-MES architecture.

During testing, the time it takes to complete the requested order after the generation of failures is measured. In the first case, the operator waits until one of the sensors at the next station where the product arrives generates an error and this is solved by intervening. In the second case, the digital system warns of the error, and the DT provides the opportunity to visualize the digital environment and replicate the behavior of the physical environment in real time, as shown in Figure 7.



(**a**)

(**b**)

Figure 7. (**a**) Digital twin–MES production line; (**b**) MES production line.

After taking the times in which each of the processes is carried out for each of the cases, the results shown in Figure 8 are obtained, where it is observed that these times are decreased by a total average of 40.2 s, which represents a percentage improvement of 14.2%. These results show that the proposed architecture provides the possibility of streamlining production and reducing downtime generated by internal or external disturbances that may occur during production.

Figure 8. Analysis of response to errors caused by the user.

4.2. AR and VR

To validate the AR and VR environments with the DT, an interaction is carried out with the elements of the manufacturing cell for the supervision, simulation, and control of certain process parameters. The system was implemented on the Unity platform where it works with the real-time data that arrive from the process; Meta 2 glasses for AR and HTC VIVE glasses for VR are used, which allow for interaction and visualization with the physical environment in real time. The AR application allows additional information to be observed so that the operator can interact with the virtual environment and allows for control of certain parameters from the glasses, enhancing the experience. In the application with VR, the operator can control and monitor the physical machine remotely through a virtual reality helmet, which provides greater mobility at work and, at the same time, maintains an immersive experience as seen in Figure 9.

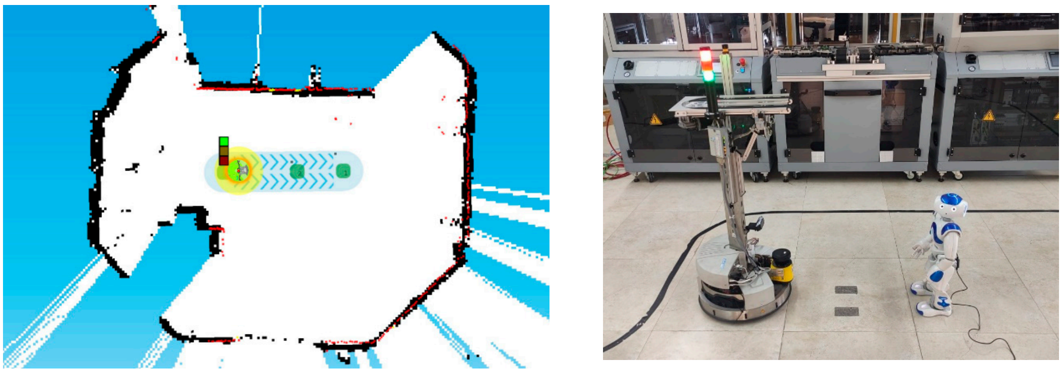
Figure 9. Physical and virtual environment with AR and VR.

Both AR and VR allow users to visualize 3D environments in an immersive way as seen in the previous figure, thus allowing fora better understanding of the process and optimization thanks to the fact that complex processes can be simulated with data obtained in real time and errors can be identified and corrected more quickly as observed in Figure 8.

Among the benefits that were evidenced by integrating AR and VR technologies in conjunction with a DT are (1) an immersive visualization and control system in real time with which users can interact and have a deeper understanding of the production line for a more accurate decision-making, (2) simulation of different scenarios and possible conditions with the real data obtained from the flexible production line, thus testing different configurations and possible evaluation of the results, and (3) optimization of the process; thanks to the benefits mentioned in (1) and (2), it is possible to achieve faster identification of errors and make more accurate configurations by knowing and understanding the process in a more real and interactive way. In addition, one of the advantages of using these technologies in the DT is that it allows for the control and visualization of the process remotely and allows for an improvement in the customer experience because it is possible to customize products according to each need without increasing production costs and with friendly systems for operators and customers. It can also be used for the training and education of operators both in industry and in the classroom where these environments allow for greater interaction and simulation with real parameters, which favors learning in technical areas.

4.3. Communication between Stations

To transport the phones between the stations, a robot that has a Lidar sensor model SICK-S300 generates the mapping and takes the best route. This mapping can be visualized in the Virtual environment and helps the operator to know the possible routes, and thanks to the continuous data received, they can plan new routes based on the conditions that can be simulated or mapped before executing the trajectory. First, the creation of a new map is carried out; by default, Robotino Factory places a brief environment in space and the user configures the environment by moving the Robotino, where it is necessary to move in all possible directions for the Lidar sensor to start performing the mapping of the physical environment and all the objects that are around it; in this way the workspace is established. It is important to consider that the minimum and maximum height must be considered when mapping. Furthermore, the system implemented in the MES allows for obstacle avoidance as shown in Figure 10.



(**a**) (**b**)

Figure 10. (**a**) Digital mapping and (**b**) the physical environment for obstacle avoidance.

When performing the trajectory analysis with the obstacle avoidance system of the conventional MES vs. the MES with the DT, it was observed that there is an improvement in route times, whereby several tests were considered by placing obstacles in the trajectory. This is because, in the conventional MES, there is a fixed distance that is programmed when an obstacle is detected. In the new system, this distance can be configured through tests carried out in the digital environment, and depending on the characteristics of the obstacle and based on the data obtained in real time, the avoidance distance can be configured. The results of the tests carried out are seen in Table 2.

Table 2. Analysis of obstacle avoidance times for the MES vs. the DT-MES.

Scenario with Several Obstacles	Mean Time (s) MES	Mean Time (s) DT-MES	Reduction in Time (s)	Reduction in Time (%)
0	25.3	19.6	5.7	22.5
1	37.5	28.1	9.4	25
2	46.1	35.2	10.9	23.6
3	59.8	47.8	12	20
4	75.3	62.1	13.2	17.5
5	87.2	71.4	15.8	18.1

As seen in the previous table, there is an average time reduction of 21.1% of the proposed system; this is because thanks to the data received by the DT, it can simulate trajectories and configure the parameters for evasion based on the characteristics of the obstacles presented, which represents a significant advantage and therefore an increase in production. The statistical distributions for the percentage of time reduction can be observed in the histogram of Figure 11, where it can be observed that the time reduction is almost similar in all cases regardless of the number of obstacles that are presented, this is due to the operation performed by the DT.

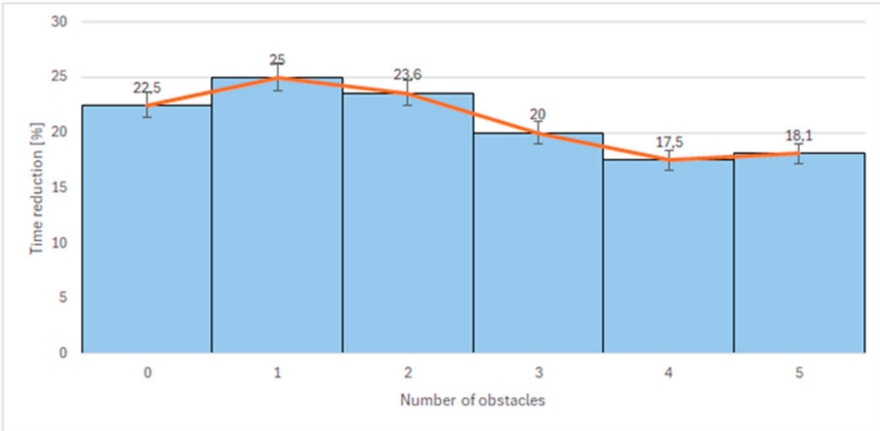


Figure 11. Histogram of the percentage of improvement of the DT-MES.

5. Discussion

From the literature reviewed, it is evident that the development of DTs has been growing constantly in different industries and universities due to the characteristics, advantages, and opportunities it presents. However, there are still several challenges such as latency, architecture standardization, and transparency protocols, among others. In 2021, the ISO committee published ISO 23247 to standardize an architectural framework to support the creation of DTs for manufacturing applications. However, it is an open framework that allows for the use of different technologies and does not prescribe specific data formats or communication protocols. It should also be highlighted that the review carried out highlights that among all the enabling technologies of Industry 4.0, the DT is the one that leads the way for complete cyber–physical integration, whereby it facilitates the integration of human–machine knowledge in different industrial cyber–physical contexts quickly and flexibly.

The present study has shown the implementation of an architecture for the implementation of DTs in Industry 4.0 where methodologies were defined to integrate new-generation and legacy equipment, several platforms were used to allow for horizontal and vertical integration of the system. The architecture was tested in an Industry 4.0 laboratory where the proposed framework for the DT was based on the ISO 23247 standard and its four application layers. The requirements that must be adhered to in the design of a DT were considered: (1) observable attributes of the manufacturing elements, that is, the elements that must be modeled, (2) the communication entity of the device that collects the state changes of the elements observable during manufacturing processes, (3) DT entities where the models of the DTs are modeled and updated based on the collected data, and (4) user entities which are applications that use DTs to make their manufacturing more efficient.

In addition, it should be emphasized that the proposal presented can be implemented in both open-loop and closed-loop systems. For digital design, it is suggested to use preset designs from a manufacturer which can then be edited and adapted to the characteristics required for the system or standard used; one can also make the 3D design of the virtual environment from scratch, and it is recommended to complete this in software that allows saving in .stl extension format for subsequent simulation and interaction through Unity with the physical environment. Regarding the physical environment, PLCs or low-cost embedded systems can be used in the control stage to control and send data from the sensors and actuators of the process; among the most used protocols that allow for bidirectional communication are OPC UA and MQTT. Finally, to allow for greater interaction with virtual environments, process data can be sent to the cloud, and from there, they can be managed for bidirectional interaction with any AR or VR technology; it is suggested to consider the number of TAGs used due to the high consumption of resources and amount of data to be processed.

The results show that the combination of immersive DT with an MES for automation and supervision increases the characteristics of these systems at both the field, process, and management levels. Where there is a virtual representation in real time with simulation and interaction capabilities between the physical and virtual entities, this allows for a faster response to internal or external disturbances that may occur during the process. This ability to model and simulate possible scenarios with real production line data allows one to reduce downtime and improve decision-making. It was also evident that the DT adapts to existing production systems to create digital data compatible with the MES; in this way, these systems can be linked. Through this integration, the process is monitored with greater efficiency and optimization, which means the total integration of digital and physical systems.

AR and VR in conjunction with DTs are innovative technologies that offer realistic environments, thus generating an immersive and interactive experience for the operator and clients, increasing the understanding of the systems, and therefore having greater precision for decision-making and reducing errors by the operator, which has a direct impact on planning and improving productivity. In addition, these systems can improve the training of operators and be used in the classroom where they allow for greater interaction and simulation with real parameters, which favors learning in technical areas. Another aspect of the results analyzed was the transportation stage between stations; this is carried out with a mobile robot that has a Lidar sensor for mapping. It was observed that the information received from the physical environment can be used for different characteristics to obtain the trajectory through simulations that are more optimal and, in this way, reduce the time required. It should be considered that one of the factors that affects transport time is the angle of vision that the robot has toward the obstacles. This angle depends on the initial and final positions in which the robot is located at the beginning and end of the process.

Some limiting factors that were revealed during the results of the study were the high consumption of computational resources and the latency presented in the cloud connection because it directly depends on the quality of the Internet. This is due to the large amount of data that the MES sends and because these data are collected from the cloud to develop AR and VR applications. To solve this problem, the main parameters that will be sent for monitoring and control from the immersive environments were selected and, in this way, communication times were reduced; also, when controlling from the virtual environment, this was immediately reflected in the physical environment and vice versa.

Within the protocols used for communication between the different levels and platforms, robustness and bidirectionality were mainly considered. Furthermore, it should be considered that the choice of a protocol also depends on the characteristics of the physical equipment. In our case, it is advantageous to use the OPC UA industrial standard because it guarantees compatibility and variability in addition to having fluid interfaces and communication in I4.0 processes, allowing communication between different devices.

However, the implementation of DTs in Industry 4.0 still presents several challenges that must be addressed, among which are: (1) the complexity and distribution of the networks that communicate the management levels due to the integration of technologies and security that the data must have, (2) performance problems that the simulation of immersive DTs has due to the high consumption of computational resources that they present, and (3) interoperability and the integration of systems and data between platforms.

6. Conclusions

The experimental results of the proposed architecture of the DT with the MES show that the system allows for interoperability between different control subsystems, improving the management and analysis of the processes through the devices of the manufacturing system. In addition, the DT allows for the detection and diagnosis of problems during the execution of the process because in the industry one of the problems presented is the internal or external disturbances that the production line may have, which generates downtime; however, thanks to the advantages of DTs, these errors can be identified faster than in the conventional system, considerably reducing times as shown in Figure 8.

Through the high-fidelity simulation and AR and VR environments provided by the DT with the data obtained in real time, manufacturing precision and efficiency can be improved through a more detailed analysis of the process, providing advantages such as interactive creation for personalized products and continuous innovation. It can also be used for the training and education of operators in industry and students in the classroom because they are interactive and safe environments, and thanks to the features, decision-making is improved, which directly benefits the optimization and performance of the production.

One of the main reasons why the OPC UA protocol was used is because of its flexibility because it allows for horizontal and vertical communication between subsystems at different levels of the automation pyramid. Therefore, by having management, process, and field levels in the MES, the protocol allows the data to be easily obtained to be sent to the DT and can allow for bidirectional communication between the physical and virtual entities.

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