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A Cyber–Physical System Based on Digital Twin and 3D SCADA for Real-Time Monitoring of Olive Oil Mills

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Abstract: Cyber–physical systems involve the creation, continuous updating, and monitoring of virtual replicas that closely mirror their physical counterparts. These virtual representations are fed by real-time data from sensors, Internet of Things (IoT) devices, and other sources, enabling a dynamic and accurate reflection of the state of the physical system. This emphasizes the importance of data synchronization, visualization, and interaction within virtual environments as a means to improve decision-making, training, maintenance, and overall operational efficiency. This paper presents a novel approach to a cyber–physical system that integrates virtual reality (VR)-based digital twins and 3D SCADA in the context of Industry 4.0 for the monitoring and optimization of an olive mill. The methodology leverages virtual reality to create a digital twin that enables immersive data-driven simulations for olive mill monitoring. The proposed CPS takes data from the physical environment through the existing sensors and measurement elements in the olive mill, concentrates them, and exposes them to the virtual environment through the Open Platform Communication United Architecture (OPC-UA) protocol, thus establishing bidirectional and real-time communication. Furthermore, in the proposed virtual environment, the digital twin is interfaced with the 3D SCADA system, allowing it to create virtual models of the process. This innovative approach has the potential to revolutionize the olive oil industry by improving operational efficiency, product quality, and sustainability while optimizing maintenance practices.

Keywords: CPS (cyber–physical system); digital twin; virtual reality; OPC-UA; smart factory; virtualization; 3D SCADA; WinCC OA

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1. Introduction

Industry 4.0, also known as the Fourth Industrial Revolution, represents a shift toward smart, connected, and highly automated manufacturing and industrial processes. It leverages digital technologies such as the Internet of Things (IoT), big data, artificial intelligence (AI), and cloud computing to revolutionize the way industries operate [1].

In this context, advanced manufacturing strategies have been initiated with the common goal of achieving smart manufacturing, where data acquisition systems and network technologies are increasingly prevalent [2]. For this reason, the concept of cyber–physical systems (CPSs), which integrate computation, communication, and control into physical processes, plays a critical role in the context of digital twins (DTs) and Industry 4.0 [3]. CPSs provide the foundational technology infrastructure that connects the physical world with the digital realm, and their role is integral to the transformation of industrial processes and manufacturing [4,5]. Connecting the functionalities between the physical and virtual worlds is a necessity to supervise, monitor, and interact with physical entities [6].

A DT is a virtual representation or digital counterpart of a physical object, system, or process. This virtual replica is created using data collected from sensors, IoT devices, and other sources, and it can simulate the behavior, performance, and characteristics of its real-world counterpart in real time or historically. In essence, a DT is a bridge between the physical and digital worlds. As such, DTs are taking a central position in new-generation intelligent manufacturing [7–9] by being integrated into CPSs [10].

On the other hand, virtual reality (VR) is a computer-generated simulation of an interactive and immersive 3D environment or experience, which can be explored, interacted with, and often manipulated by users. VR plays a significant role in Industry 4.0, where the convergence of digital technologies and the physical world transforms industrial processes and operations. The integration of DT with VR technology enhances the visualization, analysis, monitoring, and interaction capabilities of both technologies, offering new avenues for improving processes, training, and decision-making across a range of industries [11]. This convergence holds significant potential for creating more efficient and immersive experiences in various applications [12]. Linking DT and VR involves integrating the data and capabilities of digital twins into VR environments, creating a seamless connection between the virtual and physical worlds [13–15].

These technologies applied in Industry 4.0 make it possible to improve the design of new processes and products in the initial stages of development, monitor existing production processes, and create digital models of existing processes integrated within the CPS which contribute to increasing quality, reducing production costs, and preventive maintenance. DT systems are becoming a key element in Industry 4.0, although a standardized architecture for their development and implementation has yet to be defined. In this sense, research [16] has addressed the protocols and interconnection standards to create an interoperable system, digitizing the workshop through the use of the IEEE 1451 standards.

This research has addressed the development of a CPS as a real-time monitoring system for an olive oil mill, which allows optimization through the digital models provided by the DT. The information on the physical process was taken from the existing sensors and measuring equipment in the oil mill, and the DT was created based on VR techniques and integrated into the digital environment of the CPS. Within the CPS, the DT has bidirectional communication with the 3D supervisory control and data acquisition (3D SCADA) and the real environment through the Open Platform Communication United Architecture (OPC-UA) protocol, which allows the monitoring of the system and the creation of digital models applied to the virtual processes. The rest of this paper is organized as follows: Section 2 describes the literature review, Section 3 details the process of the proposed approach, Section 4 describes the implementation and results, Section 5 is the discussion, and finally Section 6 concludes the paper.

2. Literature Review

This section is divided into three sections: the first one describes the concept of the TDs, the second one details the related works, and the third one goes deeper into the innovation proposed in this study.

2.1. Digital Twin (DT)

A DT, according to [17], is a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity by using real-time and historical data to represent the past and present and simulate predicted futures. DTs allow the exchange of information from both models and directions (physical and virtual) by integrating the real context from measuring equipment and data analytics of simulated data from simulation models, achieving the optimization of manufacturing operation procedures through monitoring, prediction, and interoperability, as well as reductions in the calculation and development time of the process.

DTs could be represented in different ways; Grieves et al. [18] divided them into three subcategories: (i) Digital model (DM) in which no automatic data exchange between the digital and physical models is used. This model is disconnected from the physical layer, and the data between the physical and digital object are exchanged manually, so any changes in the state of the physical object are not reflected in the digital one directly, and vice versa. (ii) Digital Shadow (DS). In this case, the digital model obtains data from the physical model with automatic unidirectional communication, due to which any changes in the state of the physical object are not reflected in the digital one directly, and vice versa. (iii) DT, where there is an automatic bidirectional flow of data between the physical and digital objects.

On the other hand, from the perspective of smart production, according to Qi et al. [19], digital twins can be divided into three levels: unit level, system level, and SoS (system of system) level. With respect to this classification, the system-level digital twin can be regarded as the integration of multiple unit-level digital twins, which cooperate with each other, while a SoS-level digital twin is a complex system consisting of the integration of multiple unit-level or multiple system-level digital twins.

In this sense, the aim of DTs would be to mimic the behavior of the system and its relationships with the operators, components, and decision-making.

2.2. Related Work

This section provides a practical example of how DTs are integrated into CPSs to enhance manufacturing processes, increase efficiency, and facilitate data-driven decision-making. In the initial part, we will analyze the different technologies that have been used for the implementation of DTs, going into detail about the integration of DTs into CPSs, and focusing on the communication, latency, and scalability of the systems studied.

In particular, we examine the utilization of DTs through various technologies, including SIEMENS PLM, LabVIEW, 3D modeling, VR, and augmented reality (AR), among others, in a manufacturing environment. The objective is to streamline operations and acquire real-time data from the production line. Another paper [4] presents a DT, based on the simulation tool SIEMENS Plant Simulation (PS), of an industrial production line consisting of a process of qualification, verification, and assembly of pneumatic cylinders, whose main objective is to contribute to a better understanding of the inherent link between digital technologies and real hardware, as well as to optimize the process through simulation. In line with this work, the research in [20] proposes a DT through simulations performed with the PS tool for existing production systems, with the aim of obtaining data in accordance with the Industry 4.0 concept. The analysis of the data is carried out by LabWIEW, with the aim of demonstrating a more efficient Industry 4.0.

On the other hand, numerous tools have been developed to facilitate the 3D modeling and visualization of virtual environments that seamlessly converge with reality. In reference [21], an open-source architecture catering to process control, lightweight protocols, and versatile tools is introduced, employing an animated CAD model. Similarly, in [22], a high-fidelity 3D modeling approach grounded in Computer-Aided Design (CAD) is proposed. This approach utilizes software platforms such as Solidworks, Creo/ProE, UG, and Catia, alongside Unity3D, to advance the realm of custom furniture production. The outcomes of this endeavor reveal notable enhancements in production quality and efficiency, primarily attributed to real-time monitoring and the implementation of preventive maintenance strategies. In the research conducted in reference [23], a DT model is engineered for an intelligent production line, harnessing the capabilities of VR facilitated by Unity3D.

Regarding the use of AR techniques, [24] studies AR-assisted DT for the futuristic transformation of human-centered industries, concluding that the combination of AR and DT can improve the performance of industrial systems in various fields and at different stages of the engineering lifecycle. Additional applications within the framework of Industry 4.0, which are oriented towards process optimization through the utilization of DTs, are detailed in the following research studies [25–29].

An aspect worth highlighting regarding the use of different technologies is that techniques based on AR and VR not only meet the visualization and interaction requirements of the DT in a more immersive, on-site, and efficient manner but also integrate human intelligence into the DT system to achieve advanced cognitive capabilities.

With regard to the integration of DTs into CPSs, a multitude of studies have been advanced. In particular, the research conducted by [30] employed a rigorous methodology to acquire pertinent data on the physical processes, establish a digital representation of the environment, facilitate seamless communication between the physical and virtual realms, employ simulation models within the digital framework, and dynamically parameterize the simulation environment in real time based on ongoing physical processes. The utilization of an AR application was employed for the purpose of variable control, establishing an intuitive operational environment for process management. This application facilitated bidirectional communication between the physical and virtual environments, operating with an approximate latency of 100 milliseconds. In [31], a CPS is formulated for the purposes of design and control. This endeavor leverages three pivotal enabling technologies: a rapid mapping approach for distributed controllers, an extensible framework for distributed communication, and a multiscale modeling methodology. The empirical findings underscore the CPS's capacity to expedite design processes and facilitate distributed control, particularly in scenarios demanding tailored and adaptable design solutions. Furthermore, contemporary scholars advocate the incorporation of cloud technologies into the cyber layer of the CPS to ensure scalability in storage, computational capacity, and cross-domain communication capabilities. In alignment with this perspective, the investigation conducted in [32] introduces a cloud-based reference model for a CPS integrated with DT technology. Within this framework, data exchange between vehicular platoons is achieved through Dedicated Short-Range Communication (DSRC) [33] and 3G/LTE-based communication protocols. A hybrid neural network model, complemented by a sophisticated learning algorithm, is developed using simulated data to synchronize the physical and virtual systems. The findings from this research underscore the efficacy of the proposed approach, demonstrating enhanced detection accuracy for a DT deployed within a smart manufacturing context.

The seamless synchronization between the virtual reality representation and the actual physical environment is achieved through the utilization of the OPC program known as KEPServerEX, coupled with the transformation of twin data into a JSON format. It is noteworthy that an increasing number of studies have adopted the OPC-UA protocol [30,34,35] as a means of harmonizing the real and physical realms, with the overarching objective of diminishing latency times.

Within the array of studies presented, it becomes evident that the predominant challenges encompass the enhancement of bidirectional data transmission, reduction in latency, and optimization of information exchange through data analysis and digital models. An additional paramount objective entails the augmentation of the interpretability of DTs through the integration of realistic 3D models. Such a refinement would render DTs versatile tools suitable for diverse applications, including product development, process enhancement, preventative maintenance, and training within virtual environments. Consequently, the ongoing exploration and advancement of novel systems have the potential to drive the development of intelligent systems that seamlessly incorporate the DT into the CPS domain.

2.3. Research Gap

Motivated by previous studies that have highlighted the advantages of integrating DTs into CPSs, as well as the need for integration through more standard systems or architectures, this study proposes the development of a CPS based on a standardized protocol in the context of Industry 4.0 (OPC-UA), which also reduces latency times. The CPS proposed in this study is composed of a DT based on VR, which also introduces the concept of 3D SCADA, allowing for more intuitive visualization. Within the CPS, the DT acquires data through direct (bidirectional) communication with the SCADA using standardized industry protocols, simplifying and improving the integration of DTs into the CPS. The direct communication between the DT and the SCADA facilitates the simulation of digital models, as it allows parallel simulations of the environment through the DT, while the SCADA performs supervision and monitoring tasks. Furthermore, this direct communication facilitates the efficient integration and adaptation of DTs into CPSs of other plants. Therefore, this work presents innovations in CPSs in olive mills, where the digital gap still persists; the design of a 3D SCADA; and the integration of DTs into CPSs, promoting standardized architectures.

3. Proposed Approach

This section details the process carried out for the development of the CPS. The first part describes the experimental environment in which it was carried out; the second part describes the general architecture of the system, going in depth into the materials, frameworks, and protocols used.

3.1. Experimental Environment

This study was carried out in an experimental oil mill located in Andalusia (South of Spain). In this research, the existing sensors, actuators, and measuring equipment in the oil mill were used, adapting the data extraction and communication through Unified Communications (UNIFIK), the OPC-UA SERVER developed by DEUSER [36,37] and drivers for each protocol (S7, ModBus TCP, EhterCAT). Within the CPS framework, the integration of the DT and 3D SCADA enables seamless interconnectivity and interoperability, enhancing data flow and resource coordination. This allows for a greater flow of data and coordination of resources. The 3D SCADA was developed with WinCC OA (Open Architecture) of SIEMENS, and the DT was designed by creating a virtual environment based on VR technology.

The general schematic of the infrastructure is shown in Figure 1, where the integration between the physical and cyber/digital worlds through the OPC-UA protocol can be observed. In the architecture shown, the CPS, DT, and 3D SCADA form a closed loop between the cyber/digital and physical worlds, which enhances Industry 4.0 capabilities through real-time analysis, scientific decision-making, and accurate execution.

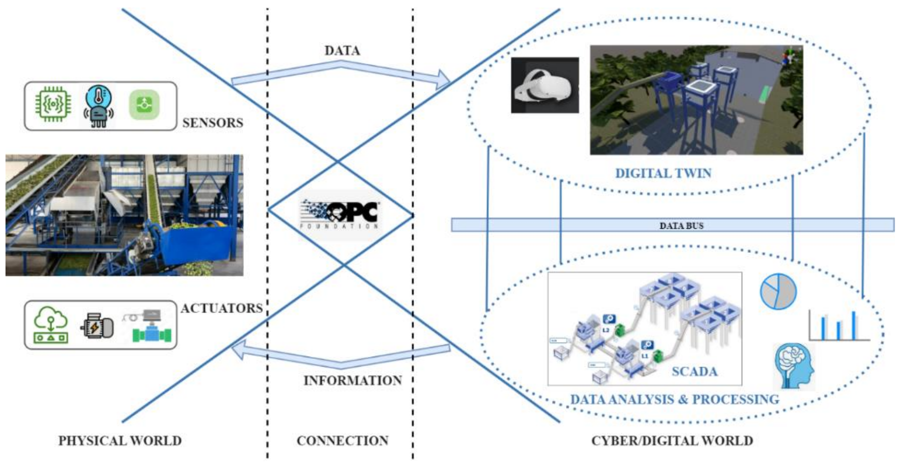


Figure 1. Designing the infrastructure between the physical and cyber/digital worlds with the integration of CPS and DT.

3.2. Design of Architecture and Framework Description

3.2.1. General Architecture

Figure 2 describes the system architecture, showing the hardware and software elements. At the physical layer, the data are collected and uploaded to the digital layer. The sensors, actuators, and measurement equipment were already part of the mill, so the focus of this research was to collect and upload data through the OPC-UA protocol. For this purpose, UNIFIK was used [37], with the S7 driver to obtain data from the PLC SIMACTIC

S7-1500, where the data from the servo-drive and motor were centralized, and the ModBUS TCP driver, to obtain data from sensors, actuators, and weighing scales. Almost all sensors were IO LINK sensors, which were connected to a master IO LINK that exposed the data through the ModBus TCP protocol. UNIFIK was installed on a PC in the oil mill, and in addition to the OPC-UA Server, a client of WinCC OA was installed on the PC (the WinCC OA server was installed in the digital layer) in order to visualize, control, and monitor all the mill data.

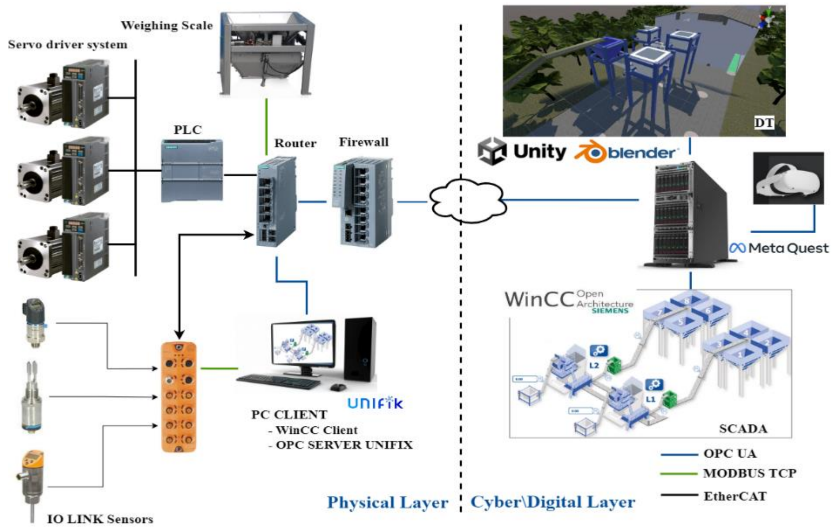


Figure 2. General architecture of the system.

The communication layer was based on the OPC-UA protocol. The server side was implemented through the OPC-UA Server of UNIFIK, and the cyber/digital layer used the OPC-UA client driver in the 3D SCADA and the OPC.UaFX library in the DT. The digital twin was developed with UNITY and Blender.

Table 1 shows the characteristics of the hardware devices used in the development. The LAPTOP MSI GE63 RAIDER 8RF was used as a Server PC in the physical layer, on which UNIFIK, drivers, and WinCC OA Client were installed. As a Server PC, the LAPTOP DELL INSPIRON was used in the cyber/digital layer, on which WinCC AO Server and UNIFIK with libraries were installed. The table also shows that META QUEST 2 was used in this research.

Table 1. Hardware devices' characteristics.

Devices	Characteristics	
MSI GE63 RAIDER 8RF LAPTOP	CPU MEMORIA RAM DISPLAY GPU	Intel i7 8750H 16 GB 3200 MHZ 1920X1080 120 HZ NVIDIA GEFORCE 1070
DELL INSPIRON LAPTOP	CPU MEMORIA RAM DISPLAY GPU	Intel i7 11800H 16 GB 3200 MHZ 1920X1080 60 HZ NVIDIA GEFORCE 3050 Ti
NVIDIA GEFORCE 3050 Ti		
META QUEST 2 VÍA AIRLINK		

3.2.2. Protocols and Framework

OPC-UA

The connection layer was created through OPC-UA, with the OPC SERVER UNIFIK. UNIFIK is a connectivity platform that securely and efficiently captures all relevant plant data in real time, both operational and energy-related, and publishes them via the OPC-UA protocol for exploitation by superordinate systems. To collect data from the mill, UNIFIK was configured with the ModBUS TCP and S7 drivers, and all data were joined and exposed via OPC-UA.

UNITY

The IDE selected for the implementation of the virtual environments was UNITY, specifically IDE Unity 2020.3.36f1 with the libraries described below:

- Shadergraph 10.10 [38] for the design of materials for the adaptation of liquids and solids to a development environment.
- Blender 3.3.1 Twin [39] for the design of the digital twin.
- MRTK 2 for UNITY [40] as a VR development kit.
- Opc.UaFx [41] for connectivity via OPC-UA through the OPC Foundation.

META 2 Glasses

The Meta 2 Glasses are a head-worn augmented reality device designed to provide users with an immersive augmented reality experience [42]. These glasses feature a transparent visor that allows users to see both the physical world and computer-generated digital content simultaneously.

To use Oculus Quest 2 in UNITY to configure and develop VR applications, the following libraries were installed: XR Interaction Toolkit, XR Plugin Management, Oculus XR Plugin, OpenXR Plugin, and Windows XR Plugin. After this, the VR scene was configured using the XR Interaction Manager object, which oversees the creation of the environment to be able to use the Oculus Quest. Finally, the Oculus Quest was connected to the computer, the goggle type and system were selected in UNITY, and the application was compiled and executed. This tool creates an environment that enables the design and prototyping of products and allows the creation and manipulation of 3D models of products, improving the design and prototyping processes.

WinCC OA

WinCC OA stands for "WinCC Open Architecture", which is an industrial and supervisory control and data acquisition (SCADA) system developed by Siemens AG. It is a software platform used for the visualization, monitoring, and control of complex industrial processes and automation systems. WinCC OA is a software platform designed for the development of customized and scalable SCADA and HMI (Human–Machine Interface) solutions in various industrial and infrastructure sectors. It provides a comprehensive set of tools and features for creating, configuring, and managing systems that collect and process data from sensors, machines, and other devices in real time. The development of the 3D SCADA for this study was performed with SIMATIC WinCC OA version 3.18 [43].

4. Implementation and Results

The core of the development of this research is a virtual environment that takes real-time data from physical processes using the OPC-UA protocol (see Figure 2). In the following sections, the developments carried out in the cyber/digital layer (3D SCADA and DT), as well as in the communication layer that allows the integration of the physical and virtual worlds, will be discussed in more detail.

4.1. Cyber/Digital Layer

The cyber/digital layer is made up of the 3D SCADA and the DT. Both have OPC-UA clients that allow real-time data to be read from the physical environment. The 3D SCADA is always monitoring the real environment, while the DT can communicate with the real environment or with the 3D SCADA in order to emulate processes.

4.1.1. 3D SCADA

The 3D SCADA allows the visualization, monitoring, and real-time control of the mill, as the SCADA processes and analyzes the data from the physical environment and generates PIDs to control the different processes. The SCADA was developed in 3D, which improves its interpretability and integration with other technologies, such as VR, which facilitates its incorporation with DT. The different modules of the mill were developed to control and monitor the different areas, specifically reception, cleaning, and grinding (under hoppers, grinder, mixer, decanter, and centrifuge) areas. The following figure shows an example SCADA screen for each of them (see Figure 3).

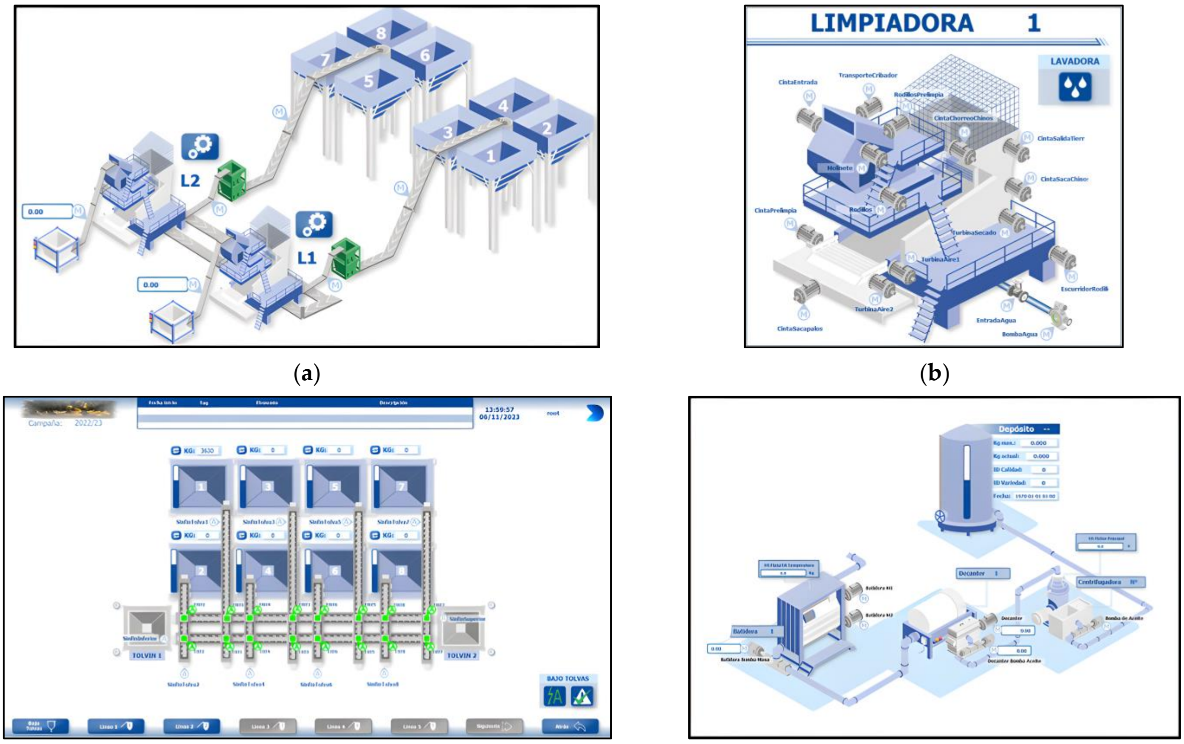
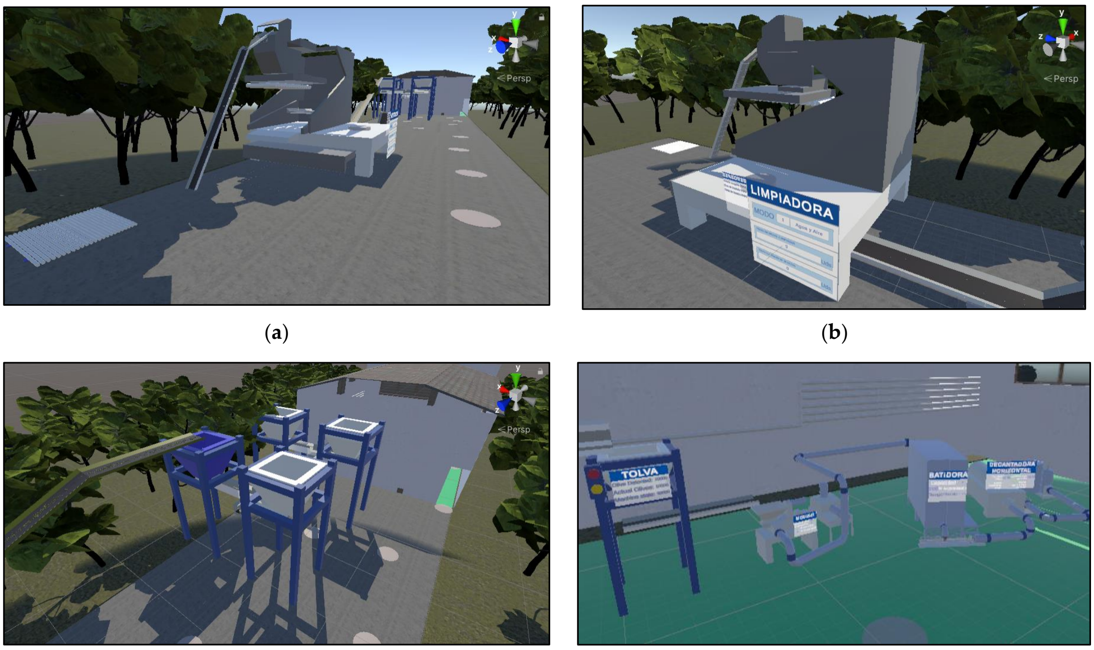


Figure 3. Detail of 3D SCADA screens to monitor different areas of the mill: (**a**) reception area; (**b**) cleaning area; (**c**) grinding area (under hoppers); (**d**) grinding area (grinder, mixer, decanter, and centrifuge).

4.1.2. Digital Twin

The DT has also been developed with VR technology, within the cyber–physical environment. Unlike the 3D SCADA (which only has communication with the physical environment), the DT has bidirectional communication with the physical environment and with the 3D SCADA. The real-time and bidirectional communication with the physical environment allows it to act in real time on the processes of the mill; therefore, in the same way as with the 3D SCADA, different real processes can be controlled, visualized, and monitored, eliminating dependence on the 3D SCADA. On the other hand, given its direct communication with the 3D SCADA, in the DT, it is possible to study behavior models of the oil mill processes through the virtual processes, i.e., the PIDs of the SCADA can act on the digital models of the twin, studying the behavior, performance, and quality of the virtual process compared to the real one, and taking those changes that imply improvements to the real process. This methodology allows procedures and changes to be tested without the need to stop the real production processes, reducing the loss of time and money that this entails. Figure 4 shows details of the different zones implemented for the digital twin, which have their counterparts in the SCADA (see Figure 4).



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

(**c**) (**d**)

Figure 4. Details of the virtual environment developed for different areas of the mill: (**a**) reception area; (**b**) cleaning area; (**c**) grinding area (under hoppers); (**d**) grinding area (grinder, mixer, decanter, and centrifuge).

4.2. Communication Layer

The central axis of the communication layer is the OPC-UA protocol, from which data are exchanged in real time between the physical and digital layers. Figure 5 shows the general scheme of the communication layer. As can be seen, data from the physical layer are acquired from the measuring equipment and sensors, which are acquired through industry protocols such as S7 and MosdBus TCP; these data are concentrated in the OPC Server (UNIFIK) which exposes them through the OPC-UA protocol. In the virtual environment, both the DT and the 3D SCADA obtain the data through different OPC-UA clients: in the DT, the client is implemented from UNITY through the OPC.UaFX library, and in the SCADA, the OPC-UA driver available with Siemens WinCC OA technology is used.

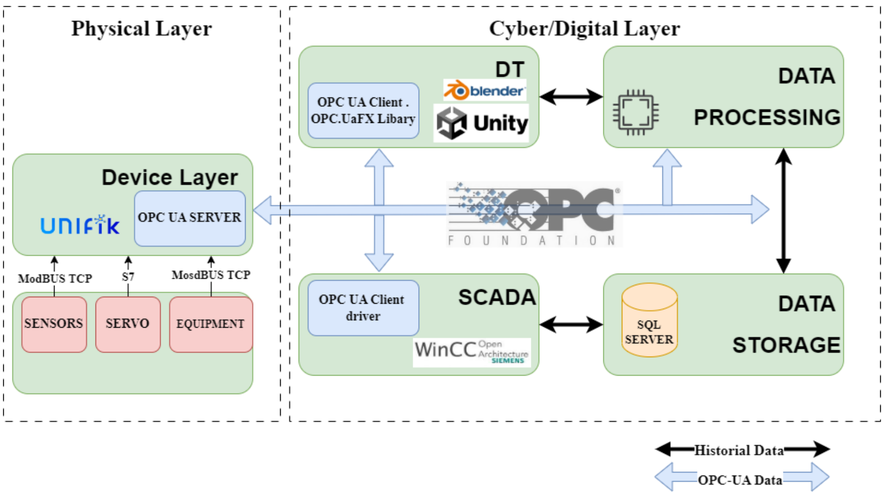


Figure 5. Communication layer overview.

The connection via OPC-UA between UNIFIK and UNITY through the OPC.UaFX library was created through the following steps: (i) detection of the environment to be connected through the OpaUaClientBehaviour script; (ii) creation of a replica of the UNIFIK OPC-UA data in the UNITY environment; (iii) generation of the nodes, in UNITY, that give access to the variables (tags). In this way, the same hierarchy of nodes and variables was achieved in UNIFIK (physical environment) and UNITY (digital environment), achieving a bidirectional communication between the virtual environment and the physical layer (see Figure 6).

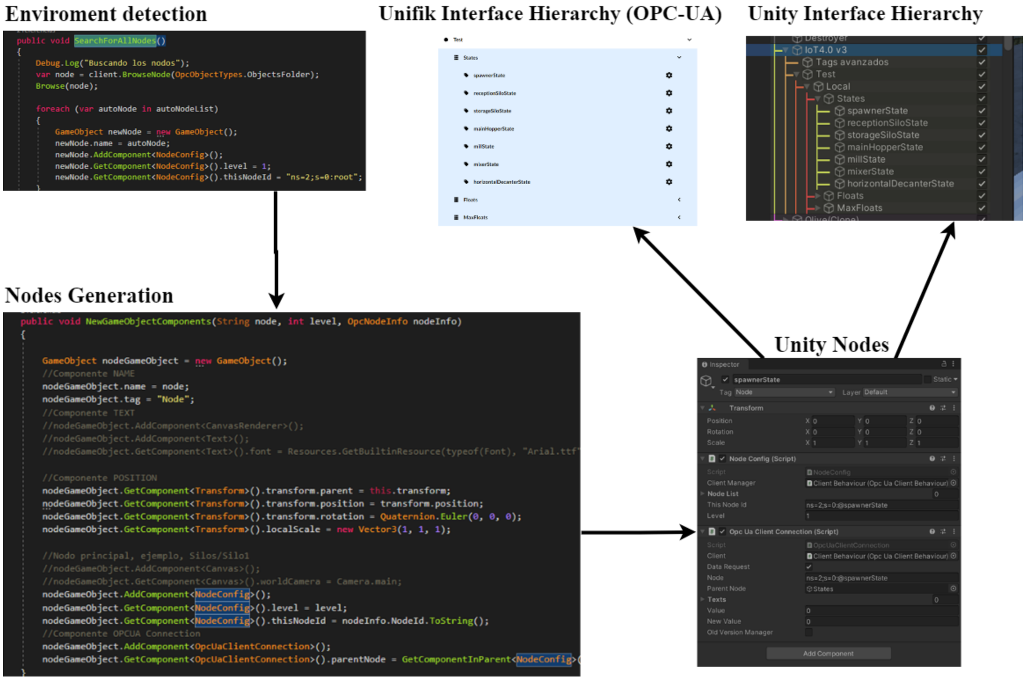


Figure 6. UNIFIK–UNITY connection via OPC.UaFX library.

Data are acquired and processed in real time by 3D SCADA and DT, but only relevant data will be stored in an SQL Server Database for subsequent modeling, analytics, and behavioral studies. This optimizes the system and makes it more sustainable.

This results in real-time, two-way communication between the physical and virtual environments via the OPC-UA protocol. The use of this protocol minimizes data latency, as data reception is around 16 milliseconds, as shown in Figure 7, and the acquisition times of a set of variables between the DT and the physical environment are monitored through the OPC-UA protocol. This allows the physical system to be monitored from both environments (3D SCADA and DT).

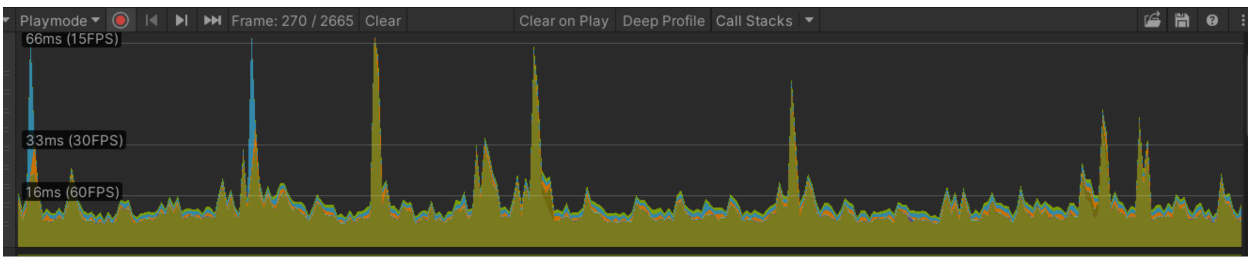


Figure 7. Monitoring of variable acquisition time between the twin and the physical environment via OPC-UA.

4.3. Case Use

In this section, a specific use case for this research will be described. As previously mentioned, this study was conducted at an olive mill located in Andalusia (Southern Spain). This facility is divided into four zones, each controlled by a specific PLC for that zone (reception, weighing, milling, and de-stoning). Next, each of the zones will be briefly described.

The reception zone consists of two reception hoppers, each associated with a set of four hoppers for depositing the product. Along the reception path is the cleaner, which, apart from separating the product from impurities, also washes the product before weighing it. After the cleaning process, the product moves to the weighing zone, where it is weighed before the milling process begins.

The milling process starts with filling the mill hoppers from one of the reception hoppers. The installation consists of two sets of four simple screw conveyors, which go from the hoppers to two reversible screw conveyors, and then to the mills. At the decanter's exit, there are two paths for extracting the product: one path leads to the centrifuge, and the other path leads to the extraction of waste that goes to the de-stoning stage. Once the product is centrifuged, it is sent, using a pump, to the storage tank where the resulting oil will be stored.

The de-stoning process is partially similar to the milling process. The valve provides access to the pomace to a screw conveyor that feeds the de-stoner. The de-stoner, which needs to work under optimal flow conditions, controls the speed of the input screw conveyor using a PID controller. During the de-stoning process, the pits are sent to one hopper and the residues to two hoppers associated with each de-stoner. Finally, the pits are extracted from the hopper using a screw conveyor or a valve to transport them elsewhere.

The following tables (Tables 2–5) show the main variables monitored in each of the zones.

Table 2. Main variables monitored in the reception area by SCADA and DT.

Reception		
Communes	**Line 1**	**Line 2**
March/stop of the zone	March/stop of the zone Rotary position Status of drives Washing machine on/off Ton/toff pulses vibro Hopper gate open/closed	March/stop of the zone Rotary position Status of drives Washing machine on/off Ton/toff pulses vibro Hopper gate open/closed

Table 3. Main variables monitored in the weighing area by SCADA and DT.

Weighing
Hopper info (status, kg, max. kg, quality, variety, start and emptying dates)
Info scales (weighed state, empty hopper, total kilos, partial kilos, weighing time, card number, quality, variety, number of weighed, hopper, supplier, farm, vehicle, party)

Table 4. Main variables monitored in the milling area by SCADA and DT.

Milling		
Under Hoppers	**Line 1**	**Line 2**
March/stop of the zone	Start/stop of the zones (grinder, mixer and decanter, centrifuge)	Start/stop of the zones (Grinder, Mixer and Decanter, Centrifuge)
Status of drives	Status of drives	Status of drives
Max. and min. hopper level	State of milling	State of milling
	Mill intensity	Mill intensity

Table 4. *Cont.*

Milling		
	Decanter main motor intensity Decanter main engine torque Decanter load cell Blender temperature Oil temperature Mass flow meter Oil flow meter Decanter speed Pomace mass pump speed Tank info (kg mass, kg oil, start date, end date, condition, quality, and variety) Configuration way (hopper, auger, mill, centrifuge, and tank)	Decanter main motor intensity Decanter main engine torque Decanter load cell Blender temperature Oil temperature Mass flow meter Oil flow meter Decanter speed Pomace mass pump speed Tank info (kg mass, kg oil, start date, end date, condition, quality, and variety) Configuration way (hopper, auger, mill, centrifuge, and tank)

Table 5. Main variables monitored in the de-stoning area by SCADA and DT.

De-Stoning		
Communes	**Line 1**	**Line 2**
March/stop of the zone Level hopper pomace Hopper level	March/stop of the zone De-stoner hopper level Deboning intensity	March/stop of the zone De-stoner hopper level Deboning intensity

5. Discussion

The main objective of this research was to conceptualize and develop a CPS for the real-time monitoring and generation of digital models of an olive mill where a DT and 3D SCADA are integrated. In this sense, a robust solution was achieved by using a 3D model, developed in the UNITY environment for the twin and WinCC OA for the 3D SCADA. This instantiation facilitates bidirectional communication, where the DT can establish connections to both the actual production system and the SCADA. This achievement constitutes the field of digital twins dedicated to the supervision and monitoring of industrial processes, an area of growing importance in the context of Industry 4.0, as underlined by the body of research exemplified by studies [28,35]. The findings of this research align with prior work, notably [21,22], where the incorporation of diverse 3D models is integral to DT generation, and more specifically with [20,23,30,34], wherein UNITY serves as the foundational platform.

The results of this work are in line with the results presented in [30], where a methodology was provided to obtain the physical process information, create the digital environment, communicate the physical environment, apply simulation models in the digital environment, and parameterize the simulation environment with the physical process in real time to obtain a digital twin supported with augmented reality, achieving a latency time between the physical and virtual entities of 100 milliseconds. Our study approach based on OPC-UA communications allowed the latency to be lowered to 16 milliseconds. This represents a significant improvement, as reducing latency in industrial monitoring systems offers significant benefits, such as real-time responsiveness to system events and anomalies, improved operational efficiency by swiftly identifying and resolving issues, enhanced decision-making precision due to updated data, and improved product quality by preventing defects in production.

Our proposal achieved real-time monitoring of the mill process through the dynamic exchange of real-time data with both the SCADA system (representing the digital world) and the physical processes (representing the real world). This achievement bears paramount significance across several domains:

- Immersive and Intuitive Monitoring: It enables real-time monitoring from a more immersive and intuitive environment, as documented in studies [42].

- Training and Skill Development: It serves as a robust training tool, providing a safe and dependable environment for skill development, a critical requirement highlighted in prior research [11,12].
- Enhanced Maintenance Practices: By facilitating preventive maintenance strategies, it contributes to the enhancement of maintenance tasks, thus bolstering operational efficiency [8].
- Digital Model Generation and Validation: The system permits the generation and validation of digital process models. The SCADA system can execute these models on the DT, allowing for rigorous validation before implementing them in the real-world environment [28]. This approach effectively circumvents production disruptions.

A current trend is the escalating adoption of 3D design principles for SCADA systems. This trend contributes to improving the interpretability of SCADAs, especially because of their closer resemblance to real-world environments. This change paves the way for the efficient reuse of these models and processes in DTs, leading to substantial reductions in development time and associated costs. This methodological approach encompasses the direct extraction of data from the SCADA system, promoting standardization and expediting the development of DT within pre-existing cyber–physical frameworks.

Among the advantages noted, the adoption of the OPC-UA protocol allows the standardization and integration of different protocols, such as ModBus TCP, S7, and IO Link, consolidating data flows under one standard. Consequently, this unification effort has culminated in a significant reduction in latency times, with a latency period of 16 milliseconds being achieved. Furthermore, integrating the DT through this protocol facilitates its adaptation to other production systems efficiently. Since it is a standardized protocol, the DT can read data from both the plant's SCADA and directly from the machinery. This is based on the industry's trend towards data exposure through this protocol, simplifying the integration process and enabling greater interoperability between systems. Therefore, this research aligns with the current trend of standardization in industrial systems.

6. Conclusions

In this research, the proposal consists of the development of a virtual environment specifically designed for the simulation of industrial oil mill processes. This simulation is carried out through the implementation of DTs, seamlessly integrated with VR technology. Within this environment, the DT is incorporated into the wider CPS, also integrated with a 3D SCADA, allowing the bidirectional exchange of real-time data between the physical and digital domains.

To improve responsiveness and minimize latency (16 milliseconds) between the real and virtual environments, the communication layer was built using the OPC-UA protocol. Based on this protocol, the DT orchestrates the exchange of data with both the physical environment, which includes machinery and sensors, and the virtual environment represented by the SCADA system. This real-time interaction with the physical processes positions the CPS as an effective real-time monitoring and simulation tool for the mill. Meanwhile, two-way communication with the SCADA system allows the DT to build virtual models of the mill's processes, thus extending its functionality and facilitating improvements in tangible production processes.

The creation of the virtual environment takes advantage of a set of tools composed of UNITY, Blender, OPC.UxUA, UNIFIK, OPC-UA clients, and an SDK adapted to META 2 Glasses. This set facilitates the development of an immersive virtual reality environment, which allows for intuitive control of the mill's processes. The integration of a 3D SCADA system, designed with Siemens WinCC OA technology, is synchronized with the 3D models created for the digital twin, with the overall aim of rationalizing, standardizing, and unifying various control systems. The communication of the DT with the SCADA system, based on established industry standard protocols, extends the potential of the VR monitoring system to cover other industrial processes and extrapolate to other areas.

This extension extends the applicability of the system to scenarios where SCADA systems expose their data via the OPC-UA protocol.

The future line of research of this work will focus on the further analysis of virtual process models generated by DT. The aim is to facilitate their integration in real time in production processes, which will allow production processes to be improved.

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