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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 to harness the power of Industry 4.0, Digital Twin technology, Virtual Reality (VR) and 3D SCADA in the context of monitoring and optimizing an olive mill. In conclusion, this paper presents a methodology that leverages digital twins and virtual reality to create an immersive, data-driven simulation and monitoring system for an olive mill. 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 a 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

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 where the common aim is to achieve smart manufacturing where data acquisition systems and network technologies are increasingly on the rise [2] or this reason, the concept of cyber–physical systems (CPS), which are systems that integrate computation, communication, and control into physical processes, enabling a seamless interaction between the physical and virtual domains [3], play a critical role in the context of the digital twins (DTs) and Industry 4.0 by providing the foundational technology infrastructure that connects the physical world with the digital realm, and their role is integral to the transformation of industrial processes

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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 behaviour, 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 CPS [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 [13,14].

These technologies applied in Industry 4.0 make it possible to improve the processes of creating new processes and products in the initial stages of development, monitor existing production processes, as well as create digital models of existing processes integrated within the CPS which contribute to increasing quality, reducing production costs and preventive maintenance. Therefore, DT systems are changing the perspective of Industry 4.0, but an architecture that standardises their development and use has not yet been defined.

This research has addressed the development of a CPS as a real-time monitoring system for an olive oil mill, which allows optimisation through the digital models provided by the DT. The information of the physical process was taken from the existing sensors and measuring equipment in the oil mill, the DT was created based on VR techniques and integrated into the digital environment of the CPS. The DT has bidirectional communication through the Open Platform Communication United Architecture protocol (OPC-UA) with the real environment and with the 3D Supervisory Control And Data Acquisition (3D SCADA) of the digital environment, which allows the monitoring of the system and the creation of digital models applied to the virtual processes. The rest of the paper is organized as follows: Section 2 describes the literature review, Section 3 presents the theoretical background, Section 4 details the process proposed approach, Section 5 describes the implementation and results, Section 6 discussion, and finally Section 7 concludes the paper.

2. Literature Review

This section is divided into two sections, the first of which details the related work, and the second of which looks in more detail at the innovation proposed in this study.

2.1. Related Work

This section provides a practical example of how DT are integrated into CPS to enhance manufacturing processes, increase efficiency, and facilitate data-driven decision-making. Specifically, we examine the utilization of DT through various technologies, including Augmented Reality (AR), SIEMENS PLM, LabVIEW, and VR, among others, in a manufacturing environment. The objective is to streamline operations and acquire real-time data from the production line. This paper [15] 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 optimise the process through simulation. In line with this work, where the objective is to go deeper into Industry 4.0 through the DT, the research [16] proposes a DT combined with existing production systems to get data according

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to the concept of Industry 4.0. The communication is carried out via ModBus TCP and OPC protocol and the analysis of the data is carried out by LabWIEW, with the aim of demonstrating a more efficient Industry 4.0. 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 [17–21].

With regard to the integration of DT into CPS a multitude of studies have been advanced. In particular, the research conducted by study [22] 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 the 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 [23], a CPS is formulated for the purposes of design and control. This endeavour leverages three pivotal enabling technologies: a rapid mapping approach for distributed controllers, an extensible framework for distributed communication, and a multiscale modelling 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 [24] introduces a cloud-based reference model for an CPS integrated with DT technology. Within this framework, data exchange between vehicular platoons is achieved through Dedicated Short-Range Communication (DSRC) [25] 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.

On the other hand, numerous tools have been developed to facilitate the 3D modelling and visualization of virtual environments that seamlessly converge with reality. In reference [26], an open-source architecture catering to process control, lightweight protocols, and versatile tools is introduced, employing an animated CAD model. Similarly, in [27], a high-fidelity 3D modelling 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 endeavour 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 [28], a DT model is engineered for an intelligent production line, harnessing the capabilities of virtual reality facilitated by Unity3D. 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 the JSON format. It is noteworthy that an increasing number of studies have adopted the OPC-UA protocol [22,29,30] 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 of latency, and optimization of information exchange through data analysis and digital models. An additional paramount objective entails augmenting 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

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novel systems has the potential to drive the development of intelligent systems that seamlessly incorporate the DT into the CPS domain.

2.2. Research Gap

Motivated by the previous studies, where the advantages provided by the integration of the DTs in the CPS, 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 within the context of Industry 4.0 (OPC-UA), which also allows for a reduction in latency times. On the other hand, the CPS proposed in this study introduces a 3D SCADA, which allows a more intuitive visualization, as well as a greater integration of more advanced technologies such as VR, simplifying and improving the integration of the DTs in the CPS. In the same line, the direct communication between the DT and the SCADA enables the simulation of digital models and the efficient integration and adaptation in other mills. Therefore, this work presents innovations in: CPS systems in olive mills, where the digital divide still persists; 3D SCADA design; and in the integration of DTs in CPS systems by promoting standardized architectures.

3. Theoretical Background

3.1. Digital Twin (DT)

DT according to [31] 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. DT allow the exchange information from both models and directions (physical and virtual) by integrating real context from measuring equipment and data analytics of simulated data from simulation models, achieving to optimization of manufacturing operation procedures through monitoring, prediction, interoperability, as well as the reduction of the calculation and development time of the process.

DT could be represented in different ways, Kritzinger et al. [32] 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, 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 an 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 object.

On other hand, from the perspective of smart production, according to Qi et al. [33] digital twin 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 twin, which cooperate with each other, while a SoS-level digital twin is a complex system consisting in the integration of a multiple unit level or multiple system level.

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

3.2. Cyber-Physical Systems (CPS)

A CPS integrates computing, storage and communication capabilities, together with object tracking and/or control capabilities in the physical world, that is, physical systems that have computational capabilities that allow them to create autonomous ecosystems. These systems are typically connected to each other, and in turn connected to the virtual world of global digital networks. In this sense, the CPS concept is conceived as a new generation, or paradigm, for future control systems, become in the backbone of the digital ecosystem requiring the ability to adapt to changing conditions with a moving target which and must be accompanied by continuous

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engineering [34]. A detailed study of their different definitions and models spectrum can be found in [35].

3.3. OPC-UA Protocol

OPC UA (Unified Architecture) stands for "Open Platform Communications Unified Architecture" released in 2008, is a platform independent service-oriented architecture that integrates all the functionality of the individual OPC Classic specifications into one extensible framework [36]. It is a communication protocol and framework designed for industrial automation and industrial Internet of Things (IIoT) applications. OPC UA is used to facilitate communication and data exchange between various devices and systems in industrial environments through interoperability, security, scalability, platform independence, historical data, real-time data and redundancy.

3.4. Virtual Reality

VR is a technology that creates a simulated, computer-generated environment that can be interacted with or explored by a person. This artificial environment is typically presented through specialized hardware, such as VR headsets or goggles, and sometimes includes additional sensory feedback, like haptic devices or motion tracking systems. The goal of VR is to immerse the user in a digital environment that feels as close to reality as possible, allowing them to interact with and experience a computer-generated world as if it were real.

There are some standards that help ensure interoperability, safety, and quality in the development and use of VR systems, among these standards we can highlight: Open XR that is OpenXR is an open standard for VR and AR platforms [37], ISO/IEC 23090-7 (Virtual Reality) which is part of the ISO/IEC 23090 standard series that focuses on coding-independent media representation for immersive multimedia [38] and, the Institute of Electrical and Electronics Engineers (IEEE) through IEEE VR Standards Working Group which focuses on terminology, performance metrics, and interoperability [39].

4. 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 has been carried out, the second part describes the general architecture of the system, going in depth into the materials, frameworks and protocols used.

4.1. Experimental Environment

The study has been 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 have been used, adapting the data extraction and communication through of Unified Communications (UNIFIK), OPC-UA SERVER developed by DEUSER [40,41], and drivers for each protocol (S7, ModBus TCP, EhterCAT). As for the Cyber/Digital world, has been integrated the DT and 3D SCADA to achieve interconnection and interoperability allowing for greater data flow and coordination of resources. This allows for a greater flow of data and coordination of resources. The 3D SCADA has been developed with WinCC OA (Open Architecture) of SIEMENS, and DT has been designed by creating a virtual environment based on VR technology.

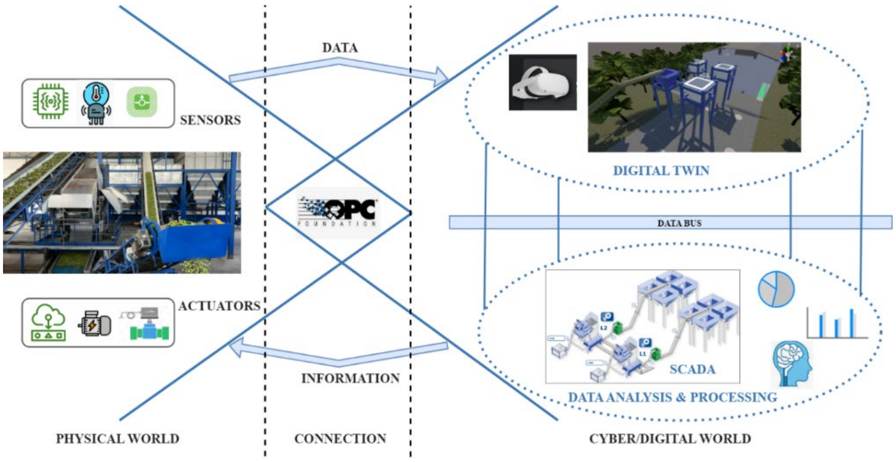


Figure 1. Designing the infrastructure between the physical and cyber/digital worlds with the integration of CPS and DT.

The general schematic of the infrastructure is shown in Figure 2, where can be observed the integration between the physical and cyber/digital world through OPC-UA protocol. 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.

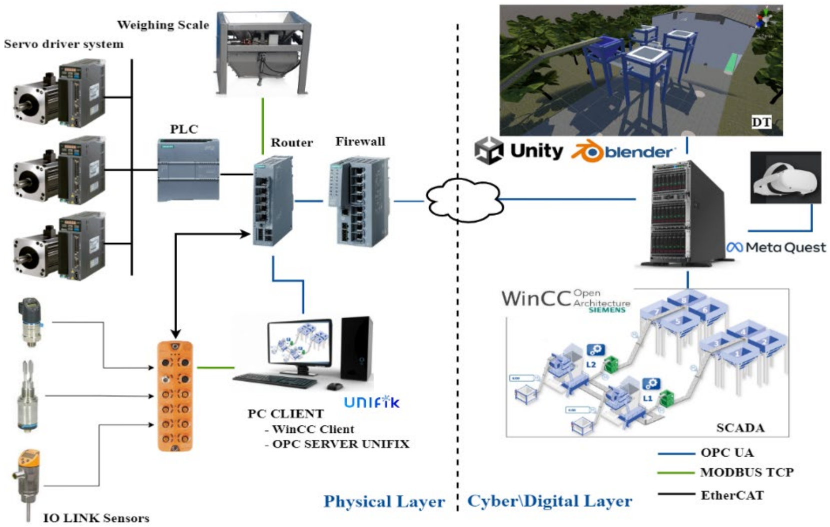
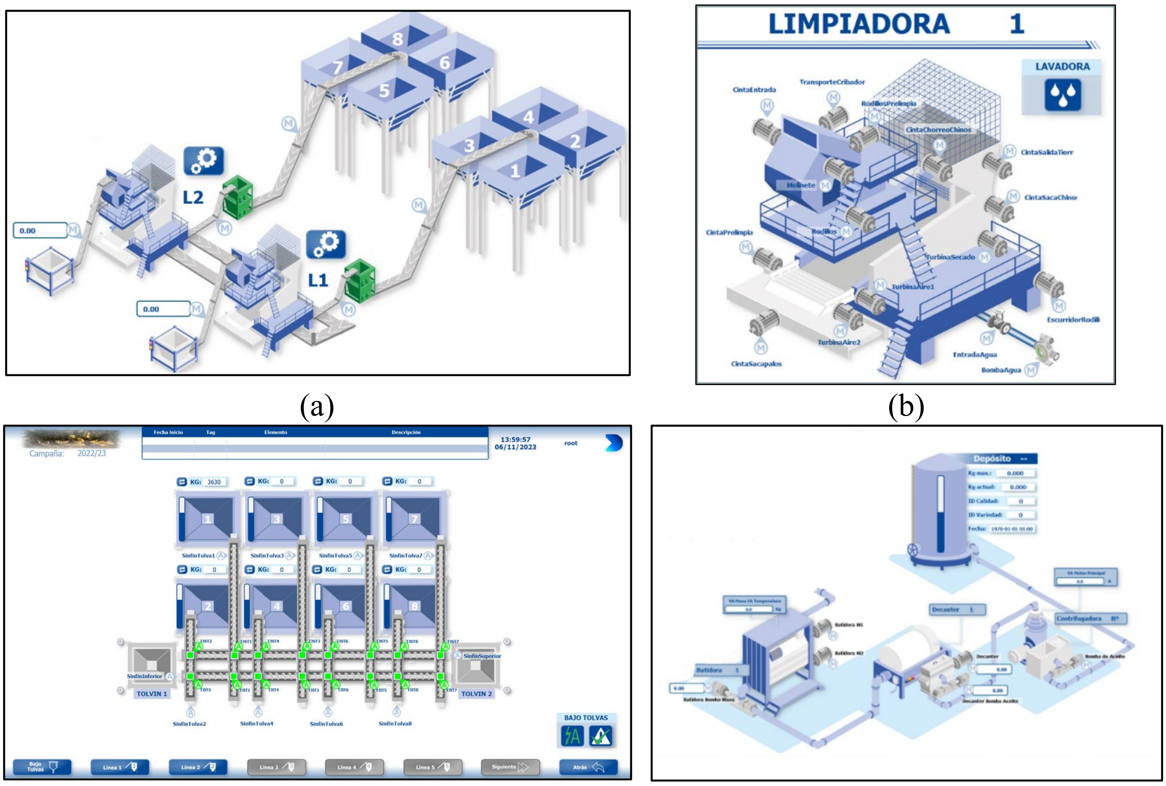


Figure 2. General architecture of the system.

4.2. Design of Architecture and Framework Description

4.2.1. General Architecture

The Figure 3 describes the system architecture, showing the hardware and software elements. At the physical layer, the data is collected and upload to the digital layer. The sensors, actuators and measurement equipment were already part of the mill, so the focus of this research was to collects and upload through OPC-UA protocol. For this purpose, the UNIFIK was used [40], with the S7 driver to get data from PLCs SIMACTIC S7-1500, where the data from servo-drive and motor was centralised, and the ModBUS TCP driver, to get 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 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 visualise, control and monitor all the mill data.



(a) (b) (c) (d)

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).

The communication layer was based on the OPC-UA protocol. The server side was implemented through the OPC-UA Sever of the 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 the META QUEST 2 used in the research.

Table 1. Hardware devices characteristics.

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

4.2.2. Protocols and Framework

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OPC UA

The connection layer has been carried out through OPC UA, with the OPC SERVER UNIFIK [41]. UNIFK is a connectivity platform that securely, efficiently and in real time captures all relevant plant data, both operational and energy-related, and publishes it via OPC UA protocol for exploitation by superordinate systems. To collect data from mill, the UNIFIK has been configured with the ModBUS TCP and S7 drivers, all data are 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 [42] for the design of materials for adaptation of liquids and solids to a development environment.

Blender 3.3.1 Twin [43] for the design of the Digital.

MRTK 2 for UNITY [44] as a VR development kit.

Opc.UaFx [45] 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 [46]. These glasses featured a transparent visor that allowed 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 creating 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, the application was compiled and executed. This tool creates an environment that enables the design and prototyping of products that 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 has been developed with SIMATIC WinCC OA version 3.18. [47].

5. 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 communications layer that allows the integration of the physical and virtual worlds, will be discussed in more detail.

5.1. Cyber/Digital Layer

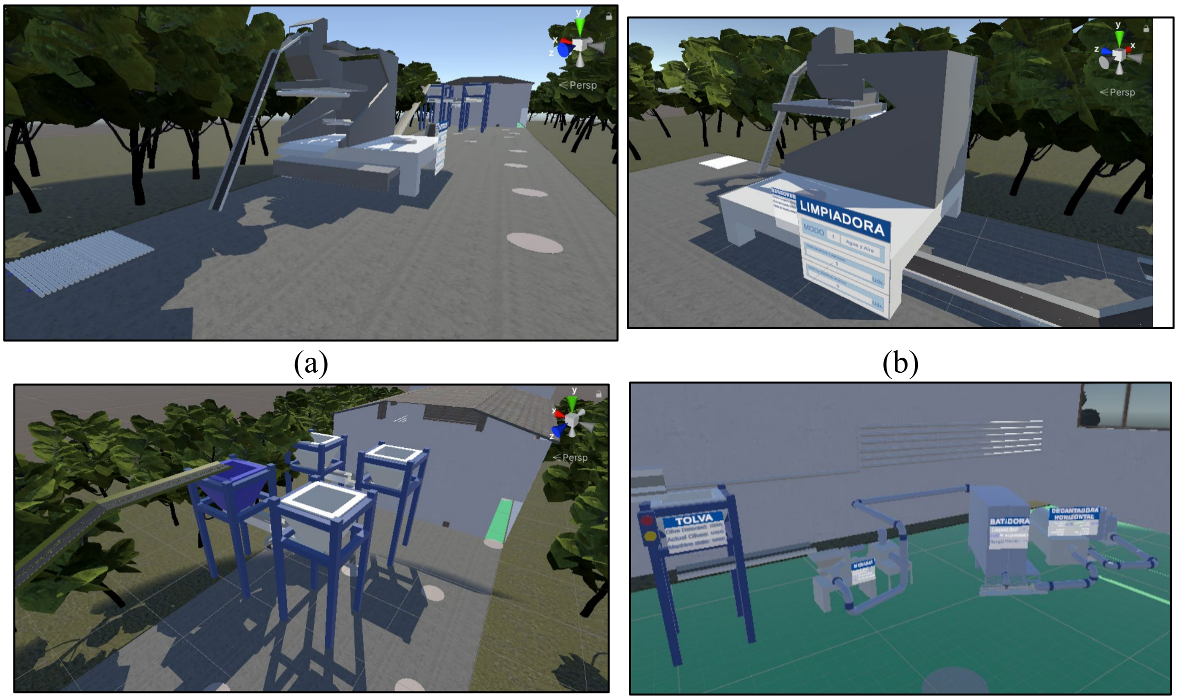
The Cyber/Digital layer is made up of the 3D SCADA and the DT. Both have OPC-UA clients that allow real-time data to be read from the physical environment. The 3D SCADA is always monitoring the real environment, while the DT can communicate with the real environment, or over the 3D SCADA in order to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

5.1.1. 3D SCADA

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

5.1.2. 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, the different real processes can be controlled, visualized and monitored, eliminating this 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 behaviour 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 behaviour, 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 SCADA.



(a) (b) (c) (d)

Figure 4. Detail 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).

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5.2. Communications Layer

The central axis of the communications layer is the OPC-UA protocol, from which data is exchanged in real time between the physical and digital layers. Figure 5 shows the general scheme of the communications 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.

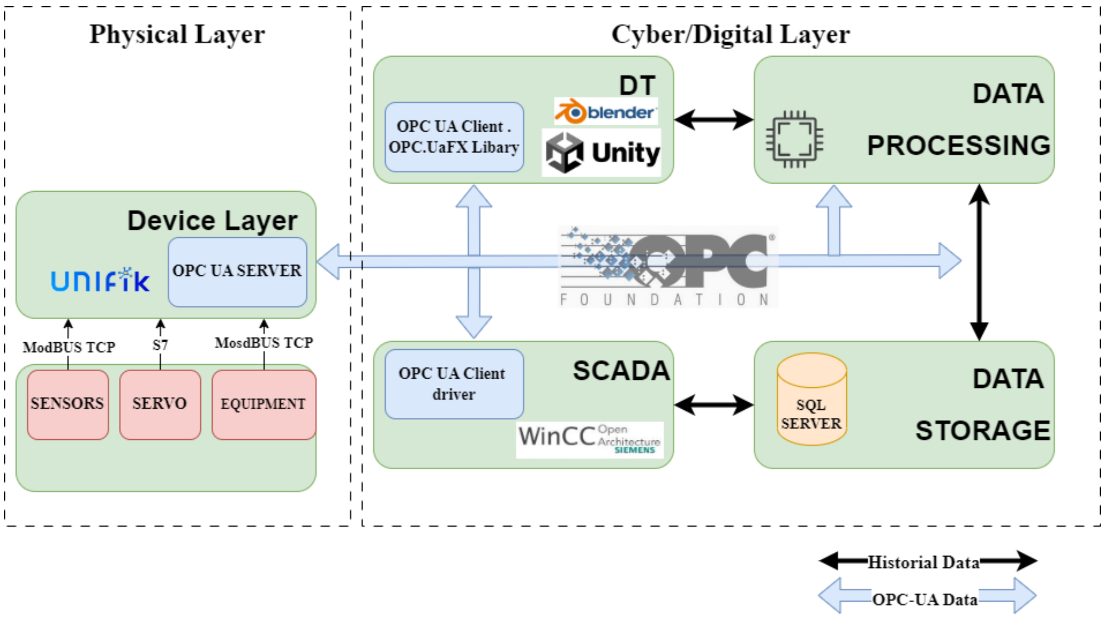

Figure 5. Communication layer overview.

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

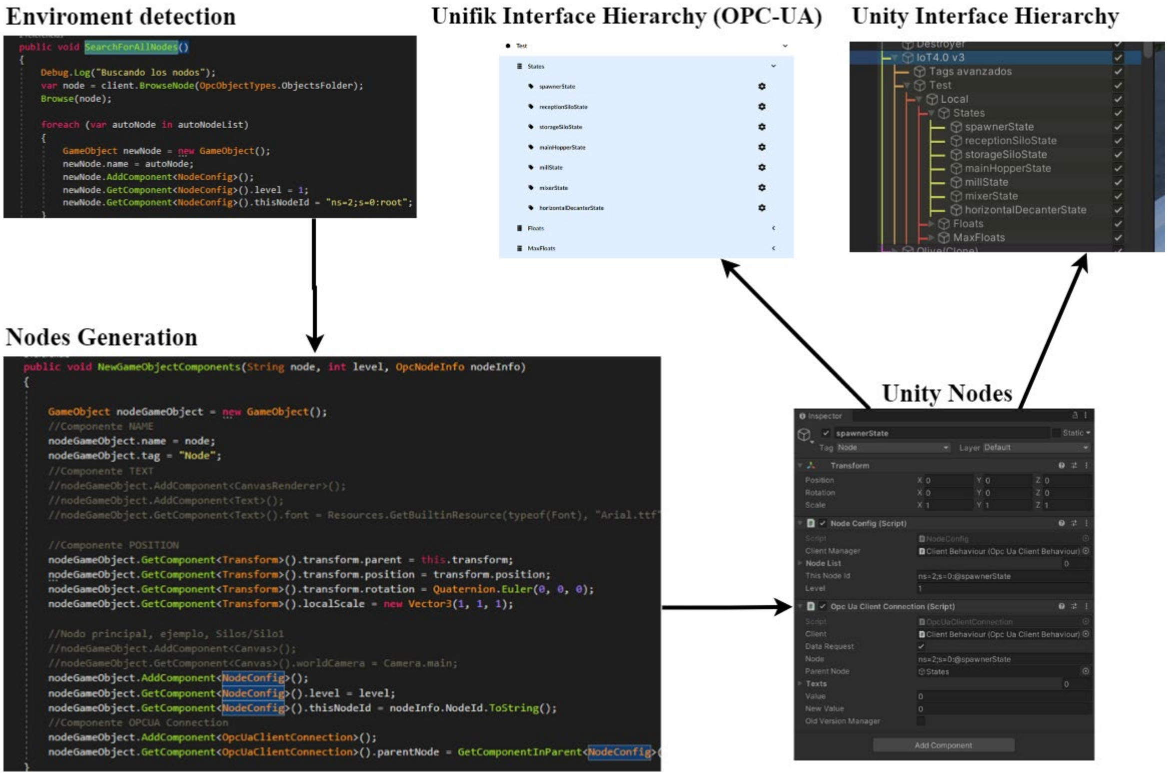

Figure 6. Unifik-Unity connection via OPC.UaFX library.

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

This has resulted in real-time, two-way communication between the physical and virtual environment 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, which monitors the acquisition times of a set of variables between the DT and the physical environment through the OPC-UA protocol. This allows the physical system to be monitored from both environments (3D SCADA and DT).

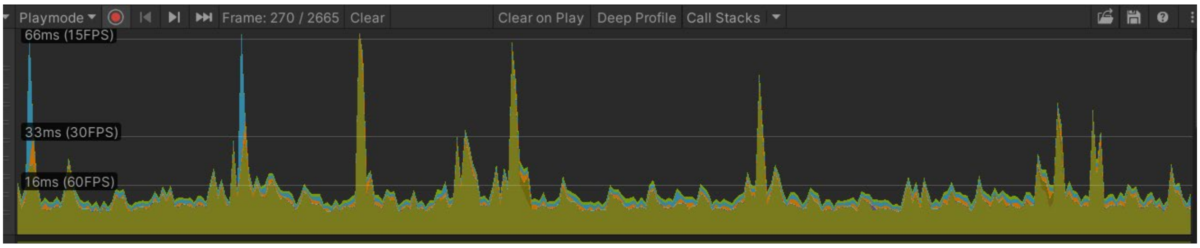

Figure 7. Monitoring of variable acquisition time between the twin and the physical environment via OPC-UA.

6. Discussion

The main objective of this research was to conceptualise and develop a CPS system for real-time monitoring and generation of digital models of an olive mill where 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 bi-directional 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[30,48–50]. The findings of

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this research align with prior work, notably [26,27], where the incorporation of diverse 3D models is integral to DT generation, and more specifically with [16,22,28,29], wherein UNITY serves as the foundational platform.

The results of this work are in line with the results presented in [22], 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 parameterise 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 lowering the latency to 16 milliseconds.

Our proposal has 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 [38,46].

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 [20]. 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 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 standardisation 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 of latency times, with a latency period of 16 milliseconds being achieved.

7. 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 has been 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 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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