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Towards the Industrial Metaverse: A proposal and preliminary validation of its architecture for immersive virtual commissioning of production systems

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Abstract: The growing demand for innovative and customized products is intensifying the need for flexibility in modern production systems, emphasizing the relevance of rapid validation before their physical commissioning. To address this challenge, virtual commissioning has emerged as promising solution. In this context, this study proposes an immersive virtual commissioning architecture that extends traditional approaches of virtual commissioning. Specifically, it introduces the validation of human-machine interactions as an additional element of the traditional virtual commissioning process, by enabling active human involvement during simulations via Virtual Reality. A preliminary validation of the architecture is conducted in a laboratory setting, where the logical and kinematic behaviors of a production machine, along with human-machine interactions, are tested. The immersive virtual commissioning architecture contributes to improve production systems design by incorporating human-machine interactions validation prior to the physical installation, unlike current practices, which address this aspect only after the physical deployment. Future work should investigate comparative analyses against existing virtual commissioning architecture to demonstrate the benefits of active human involvement and to quantify improvements in cost and time through application in industrial contexts.

Keywords: Virtual Reality, Virtual Commissioning, Production System, Design, Human-Machine Interaction, Industrial Metaverse, Manufacturing

1. INTRODUCTION

Mass customization and increasingly shorter product life cycles are placing growing demands on modern production systems, which must become more flexible and adaptable to accommodate diverse and rapidly evolving customer requirements (Mindas and Bednar, 2016). As automation remains a cornerstone of these systems, the need for rapid validation of control logic has become more pressing (Ullrich et al., 2024). To address this, virtual commissioning and digitalization have emerged as leading transformative approaches (Ullrich et al., 2024).

Virtual commissioning refers to the simulation-based validation of control logic and kinematic behavior of production systems prior to their physical deployment (Lechler et al., 2019). This method has been largely adopted due to its potential to reduce time-to-market and costs in the design of production systems (Konstantinov et al., 2022). In response to its growing importance, several frameworks have been developed to support effective virtual commissioning (Lechler et al., 2019). Current frameworks primarily focus on validating system control logic and corresponding kinematics, while human-machine interactions (HMIs) are typically not assessed in an interactive or immersive manner. Indeed, these interactions are usually tested only after the physical system has been installed (Xu et al., 2024), which can lead to costly rework and inefficiencies if ergonomics or functional issues arise.

Anticipating these interactions earlier within the virtual commissioning phase, by enabling human operators to interact with HMI panels in immersive environments, could mitigate such risks (Dammacco et al., 2022). In this regard, recent studies have explored the integration of Virtual Reality (VR) and Augmented Reality (AR) into virtual commissioning, enabling limited forms of human involvement during simulations (Ullrich et al., 2024). However, current applications generally assign humans a passive role, focused mainly on improving visualization of machine movements and kinematics (Xu et al., 2024).

The rising of the Industrial Metaverse (IM) concept offers new opportunities to actively engage humans in simulation-based processes (Dammacco et al., 2022; Guo et al., 2024). The IM envisions immersive environments in which human operators are not merely observers but active participants, capable of directly influencing the virtual commissioning process.

In response to this potential, this study proposes an architecture for immersive virtual commissioning of production systems. The proposed architecture extends conventional CAD/CAE-based approaches by actively involving human operators in the simulation, enabling validation of HMIs and enhancing machine kinematics within immersive virtual environments. A preliminary validation conducted in a laboratory setting demonstrates the feasibility of this approach and provides a foundation for future applications in industrial contexts.

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After discussing previous related works in Section 2, Section 3 presents the architecture for conducting immersive virtual commissioning. Section 4 illustrates its proof-of-concept implementation in the laboratory, while Section 5 discusses implications of the proposed architecture. Finally, Section 6 draws conclusions of this work and future research avenues.

2. BACKGROUND AND STATE OF THE ART ON IMMERSIVE VIRTUAL COMMISSIONING

Virtual commissioning is one of the final steps in the design of production systems aiming at validating their control logic through simulation and computers (Figure 1) (Lechler et al., 2019). This process has been widely adopted to achieve significant time and cost savings in the design of production systems by testing and debugging PLC logic prior to their physical commissioning (Konstantinov et al., 2022).

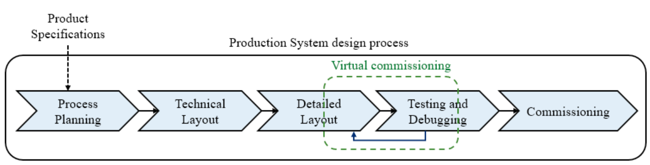

Figure 1: Focus phase of virtual commissioning in production system design process [inspired from Konstantinov et al. (2022)]

In recent years, digital technologies like DT and VR/AR have been integrated into virtual commissioning workflows to improve their efficiency (Christ et al., 2023; Ullrich et al., 2024; Xu et al., 2024). In this regard, when physical systems are not yet installed, DT refers to the creation of digital models that are designed with the future synchronization between physical and virtual objects in mind (Barbieri et al., 2021). Meanwhile, AR has been employed to create virtual-real fusion environment, where physical equipment can be seamlessly integrated with virtual counterparts to support the commissioning process when production systems are physically installed. This approach enables the involvement of active roles of humans through AR technologies (Xu et al., 2024). Likewise, VR technologies have also been proposed to streamline virtual commissioning processes by enabling comprehensive validation of machine components (Dammacco et al., 2022). Thus, integrating these technologies in virtual commissioning allows safer environments to test the interaction between operators and machines, as well as logic and kinematics of production systems prior to their physical deployment.

Recent work has begun explore the concept of the IM, conceptualized as integrated use of DT and VR/AR (Qian et al., 2024). In this regard, some architectures have been recently developed. Kim and Jeong (2022) developed an architecture based on three interconnected layers characterized by the cyber-physical synchronization between physical and visualization layers, accessible through VR headsets, for supporting collaborative design processes in virtual environments. Wenzheng et al. (2023) proposed a three-layer architecture comprising infrastructure, core, and application layers, where data are collected through sensors in the first layer, virtual systems are modeled and simulated in the core layer using DT, AI, and cloud computing, and the application layers aimed at providing the decision-making process. Guo et al. (2024) introduced a five-level system architecture describing the rationale of the IM alongside triple flows of information among the five levels, which enable the connection between physical and virtual spaces. Ullrich et al. (2024) proposed an IM-based architecture focusing on integrating PLC code through a communication layer to virtually commission multiple interconnected DTs. Similarly, Tu et al. (2024) outlined a novel IM architecture composed of a physical space and a metaverse space, enabling their real-time synchronization by means of semantic link and DTs.

Although the promise of integrating VR/AR technologies into DTs and digital models for virtual commissioning to improve kinematic analysis of machines (Ullrich et al., 2024; Xu et al., 2024), existing studies remain limited in their exploration of architectures that enable immersive virtual commissioning processes. In particular, there is a lack of focus on architectures that actively involve production operators in validating control logics of HMI through immersive and interactive experiences.

3. PROPOSAL OF AN IMMERSIVE VIRTUAL COMMISSIONING ARCHITECTURE OF PRODUCTION SYSTEMS

This section proposes an architecture for conducting immersive virtual commissioning of production systems, with a view toward the IM. It introduces a novel approach that enables humans to play active roles specifically in the validation of HMIs, while also supporting the validation of control logic and enhancing kinematics of production systems.

The proposed architecture (Figure 2) illustrates the integration of various software and hardware components, along with information flows, to effectively support immersive virtual commissioning of production systems. The architecture is structured into two domains: the virtual space and the physical space. While the primary focus of this work is on virtual commissioning, conducted independently of the physical space, the architecture also highlights how the physical space is shaped as a result of the virtual commissioning process. Moreover, since operators are actively involved in validating HMIs within the virtual environment, their inputs contribute to defining and justifying the configuration of the physical space throughout the virtual commissioning process, making its representation meaningful even before physical implementation.

The physical space is shaped based on validation outcomes derived from simulation conducted in the virtual space, which functions as the testing environment for the design of the physical systems. Indeed, dashed arrows in the architecture refer to the outputs from the virtual commissioning process, which lead to the final definition and installation of the physical PLCs and production system.

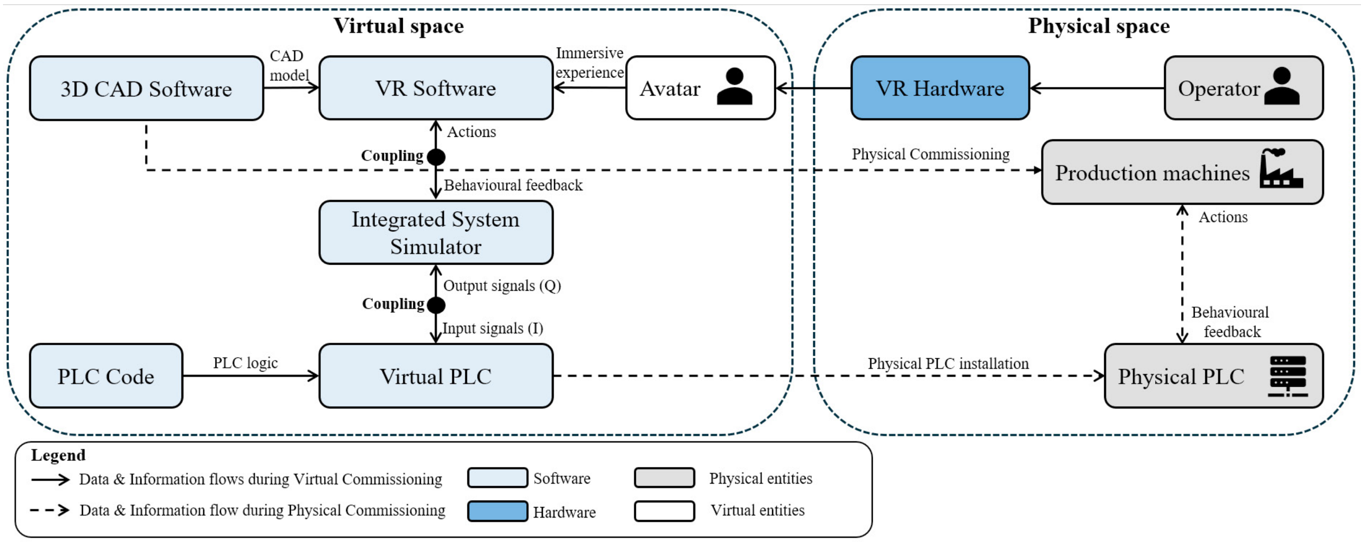

Figure 2: Proposed architecture for performing immersive virtual commissioning processes: main elements, blocks and information flows

3.1 Virtual Space

The virtual space represents the core environment where the virtual commissioning process takes place and comprises the following entities:

- *PLC Code*: program aimed at governing the operations of the PLC, a core digital component in industrial automation designed to monitor inputs, logic-based instruction, and outputs of an automated machine or system. Within virtual commissioning processes, this refers to the source code that needs to be validated through simulations and, eventually, modified to ensure correct machine behavior;
- *Virtual PLC*: software-based emulation of the future physical PLC, enabling users to design, test, and debug control logic without relying on physical hardware;
- *Integrated System Simulator*: tool used for simulating virtual PLC logics through behavioral models;
- *3D CAD Software*: digital tool used in the proposed architecture to create detailed 3D models of production machines;
- *VR Software*: software used to develop the virtual environment. It must support HMI to provide users with effective immersive experiences, 3D CAD import functions, as well as the coupling network with the Integrated System Simulator;
- *Avatar*: digital counterpart of the user inside the virtual environment.

The PLC Code represents the starting point of the virtual commissioning process, as it embeds the logical behavior of the various production machines that need to be validated. This code is hosted within a Virtual PLC, which is simulated with the aim of replicating the behavior enclosed in the code through actual movements of components in the virtual environment realized within the VR Software. In this virtual environment, the operator can lead immersive experiences and interact with virtual objects and machines through a digital avatar, providing the opportunity of validating HMI logic such as emergency button or protective barriers.

The Integrated System Simulator represents the core entity of the architecture, as it manages the interfaces with the Virtual PLC and the VR Software. It receives output signals (e.g., PLC commands, control signals to move components) from the Virtual PLC and sends back input signals (e.g., sensor states, analog values). In this way, it can translate output signals into actions of various production machine components in the virtual environment realized through the VR Software. The virtual environment is composed of the various 3D digital models of the production machines, imported in the VR Software from a 3D CAD Software. The virtual environment sends back to the Integrated System Simulator behavioral feedback, including current states (e.g., position, completion of an action) and simulated events caused by HMI, to close the loop and handle the whole PLC logic.

3.2 Physical space

The physical space, which is shaped based on results from virtual commissioning, is composed of the following entities:

- *Physical PLC*: logical behavior of the production machines established after the virtual commissioning process, involving also sensors and actuators needed for its correct operations;
- *Production machines*: physical assets responsible for executing specific production processes, which will be designed based on the outcomes from the virtual space;
- *Operator*: line or production operator tasked for operating and/or monitoring the machine production process. In industrial environments, the operator has to follow predetermined safety protocols, which can be also partially embedded in the PLC code;
- *VR Hardware*: set of equipment necessary for enabling immersive experiences for operators (e.g., VR headset, computer).

The physical space includes the resources required to carry out the production activities once the production system is commissioned. Only the operator, with the VR Hardware, takes part in the virtual commissioning process. Indeed, the inclusion of the operator and VR hardware represents one of the most relevant novelties introduced to virtual commissioning processes enabled by the proposed architecture. This allows the simulation of production machines behavior while actively involving operators in the virtual environment. This integration enables the validation of PLC code associated with HMIs, in addition to the automation related to the machine, all prior to the physical installation of the production machines.

4. PROOF-OF-CONCEPT OF THE PROPOSED ARCHITECTURE AT LABORATORY SCALE

The applicability of the proposed architecture is demonstrated through a preliminary validation in the Industry 4.0 Laboratory at Politecnico di Milano. The laboratory is equipped with a semi-automatic assembly line composed of 7 stations and designed to realize simplified mobile phones.

This proof-of-concept aims to verify the validity and applicability of the proposed architecture on the Drilling Station through the validation of its virtual PLC. This station is designed to create two holes on the left and two holes on the right side of the front cover transported by the pallet.

The steps performed to build and validate the architecture are illustrated in Figure 3 and described in the next sub-sections.

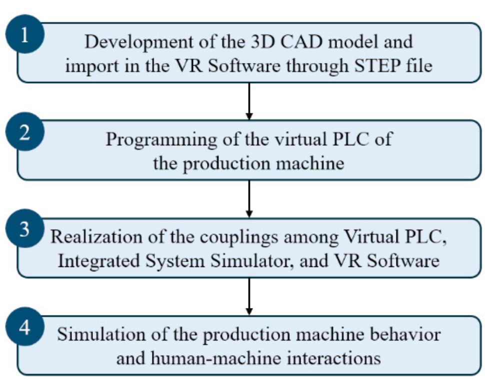

Figure 3: Process followed to build the proposed architecture

4.1 3D CAD model development

The first step for realizing the proposed architecture is to develop the 3D CAD model of the Drilling Station (Figure 4) in Siemens NX MCD. The CAD model incorporates all the sensors and actuators needed for the station to work, with their names aligned consistently with those in the PLC code. This ensures a seamless correspondence and match between the hardware of the station and its actual movements in the virtual space. As shown in Figure 4, the drill unit is movable along two axes:

- *Drill X-axis*: needed for moving the drill unit between the left and the right sides. The two limit switches on this axis lead to a change of the Boolean values of *xVN_BG1* and *xVN_BG2* in order to control the X-axis movement;
- *Drill Z-axis*: needed for moving the drill unit between the top and bottom stops. The two limit switches on this axis lead to the change of the Boolean values of *xVN_BG5* and *xVN_BG6* in order to control of the Z-axis movement.

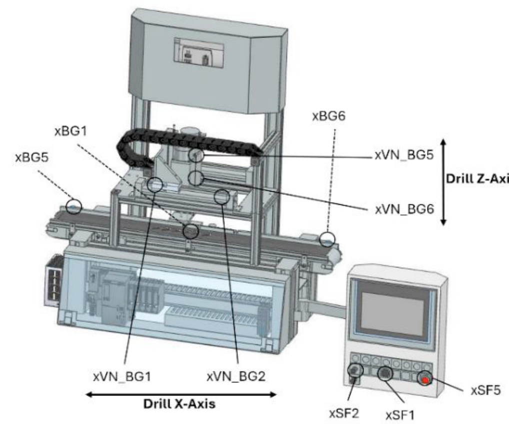

Figure 4: 3D CAD model of the Drilling Station

The sensors xBG5, xBG1, and xBG6 govern the movement of the conveyor based on their Boolean values. Regarding the HMI panel of the production machine, the button xSF5 manages the emergency stop function, while xSF1 and xSF2 are used to control the start and stop functions, respectively.

The STEP file format has proven to be an effective means for importing CAD models into Unity environment, enabling functionalities such as editing, repositioning, and modifying individual components. This includes assigning specific behaviors and attributes, while preserving the native assembly structure. However, kinematic information and assembly constraints are not retained during import. Indeed, dedicated scripts must be developed within Unity to replicate the kinematic behavior of components. These scripts need to be individually associated with each relevant part to accurately simulate motion and interactions. While the animation and kinematic of parts are managed by Unity, the logic of those movements is handled by the PLC logic.

4.2 PLC code programming

The PLC code has been programmed in TIA Portal through ladder language. Then, PLCSIM Advanced software allows the extension of TIA Portal capabilities by realizing a virtual PLC based on the written code. This code is able to replicate logical behaviors of the Drilling Station.

The selection process of this pool of software is based both on the maturity of the Siemens ecosystem in supporting such kind of processes based on automation and the presence in the laboratory of a Siemens PLC.

4.3 Realization of the couplings

SIMIT has been chosen as Integrated System Simulator software since it enables its coupling both with the virtual PLC realized in PLCSIM Advanced and Unity environment, which is selected as VR software due to the possibility of its coupling with SIMIT. These two couplings allow to exchange signals and behavioral feedback, as well as the translation of PLC commands into actions to the virtual model in Unity. Likewise, Unity has been selected for its high visualization performance, the possibility of analyzing HMIs through VR, and as just stated, the presence of a coupling point with SIMIT.

4.4 Simulation and PLC code validation

The final step is to validate the PLC logic through the concurrent simulation in Unity, SIMIT, and PLCSIM Advanced, which enabled the movements of the Drilling Station components based on the PLC logic. Figure 5 presents an excerpt of the SIMIT behavioral model (left), which manages the exchange of signals and feedback between the virtual PLC and the Unity environment, and the Unity scene (right), where the virtual station has been imported to enable immersive, interactive experiences via VR and enhanced visualization. The user immersive experience has been allowed by Meta Quest 3 as VR hardware, which enabled HMI within Unity.

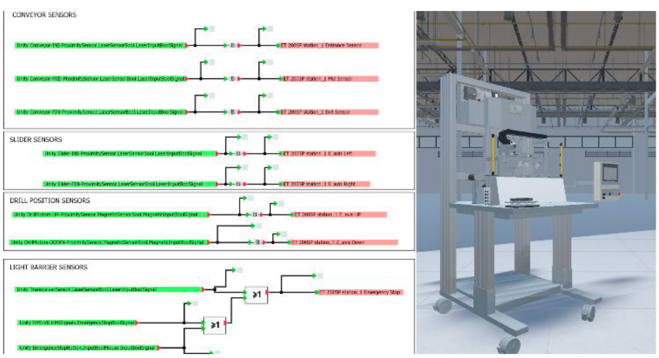

Figure 5: Excerpt of SIMIT and Unity simulation environments

The validation of the PLC logic by the proposed architecture has been realized through the following two steps:

- Verification of all HMIs of the station, testing the functionality of the emergency button, the start button, and stop button;
- Evaluation of the Drilling Station operations in the virtual environment, ensuring they match those of the physical station.

While the first validation step is related to one of the main novel features brought by the proposed architecture, which is to foster the active role of operators in the virtual commissioning process, the second step is possible since the station considered for the validation is installed and physically available in the laboratory. Thus, the second step aimed at reinforcing the validity of the proposed architecture, given its verification even with the existing physical machine. Evaluating this second step means not only to verify the validity of the proposed architecture but also to demonstrate its ability to correctly replicate the real behavior of the physical machine available in the laboratory.

5. DISCUSSION

The virtual model of the Drilling Station is demonstrated to be fully visible and interactable using the VR headset in Unity, providing an immersive experience where the station operates realistically, based on the PLC logic. This setup allows for detailed technical reviews and user interaction, as planned from the objective of this proof-of-concept. This application aims to showcase the feasibility of building an architecture to support immersive virtual commissioning during the design of new production systems.

In general, the proposed architecture has the potential to empower the role of humans in the design process from both operational and strategic perspectives. On the one hand, this architecture allows the involvement of production operators directly in the virtual commissioning, fostering a validation process of the logical and kinematic behaviors while incorporating HMIs alongside the actual movements of the machine. On the other hand, although this architecture is not specifically designed for stakeholder collaboration, it does not limit it. Indeed, if integrated with suitable infrastructures, such as collaborative platforms or multi-user VR systems enabled by Unity capabilities, it can support immersive experiences for multiple actors during the design phase, even remotely. This enables stakeholders to discuss design configurations before physical systems exist more efficiently and improves understanding of aspects that may be difficult to interpret using traditional 3D CAD tools.

The integration of humans into the virtual environment from the design process can bring several benefits. The proposed architecture demonstrated the possibility of validating HMIs prior to the physical implementation of the production system. This enables the anticipation of design concerns from the outset, enhancing the overall efficiency of the design of production systems by minimizing wasted time and cost derived from design iterations and reworks.

6. CONCLUSION

This paper aimed to showcase the feasibility of implementing an architecture for immersive virtual commissioning processes in production systems design, extending traditional virtual commissioning with active roles of humans during simulation in testing control logics of HMIs.

The proposed architecture is composed of a virtual space, which shapes the physical space as a result of the virtual commissioning process based on testing and simulation of virtual PLC logic of production machines. The immersive virtual commissioning process, in the proposed architecture, ensures not only the validation of the logical and kinematic behavior of the machine movements but also the validation of HMIs integrated in the PLC code via immersive and interactive VR experiences. In this regard, the proposed architecture enhances the scope of traditional virtual commissioning architectures, performed through CAD/CAE software, by involving humans with active roles during simulation to test HMIs.

The active involvement of the humans within the simulation in the virtual environment is considered one of the main novelties allowed by the proposed architecture. Indeed, it integrates the possibility of anticipating design decisions of the production system prior to its physical installation, achieving benefits in terms of associated time due to a reduction in reworks. This setting also lays the foundation for training of operators in VR prior to the physical realization of the production system.

In the preliminary validation proposed in this work, the PLC logic lacks the integration of the interaction between the production machine and the information system. Furthermore, only one single machine of the entire line has been included in the PLC logic validation. Introducing these aspects in the next future can lead to a more comprehensive immersive virtual commissioning process towards the realization of the IM.

This paper opens the way for future research in this area. Future work should explore alternative approaches for developing and implementing immersive virtual commissioning architectures within the design process. Comparative studies with both traditional and immersive virtual commissioning frameworks could provide valuable contributions to the optimization of such process. Moreover, future research endeavors should investigate possible infrastructure to foster collaborative design processes from different geographical locations during virtual commissioning. Finally, the proposed architecture needs to be tested in industrial setting applications, potentially providing quantitative results in terms of improvements in error detection, debugging efficiency, time-to-market reduction, and cost savings.

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