

Development of a 3D Environment for Digital Twins in an Advanced Manufacturing Didactic Plant

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The monitoring, analysis, and optimization of industrial processes are crucial for improving productivity and efficiency in industrial environments. A significant challenge is the need for effective platforms that allow for scenario simulation, training, and predictive maintenance in real-time. Addressing it, this work proposes the development of a 3D environment for the creation of Digital Twins in an Advanced Manufacturing Didactic Plant. The objective is to provide a platform for scenario simulation, training, and predictive maintenance, contributing to the optimization of productivity and efficiency in industrial environments, while specifically, it develops a digital model that accurately represents the physical environment of the didactic plan, facilitate the simulation of real-world scenarios for process optimization and operator training and ensure seamless integration with the plant's existing Programmable Logic Controllers (PLCs) for real-time data acquisition and control .

Keywords: Digital Twins. 3D Environment. Advanced Manufacturing Didactic Plant. Industry 4.0.

Industry 4.0 has driven the integration of advanced technologies, such as digital twins (DTs), to optimize processes and increase efficiency in manufacturing. DTs emerge as a transformative tool, offering a dynamic and interactive virtual representation of physical assets. This representation allows for real-time monitoring, predictive analysis, and optimization of operations, as highlighted by [1]. The ability to simulate scenarios and predict behaviors makes DTs indispensable for strategic and tactical decision-making, resulting in significant savings for organizations. The development of immersive 3D environments is a useful component for the effectiveness of Digital Twins, as it facilitates interaction and data visualization in a more intuitive context.

Papers [2] on 'on-the-fly' 3D environments for open-source immersive DT applications, and [3] on the practical implementation of an Augmented Reality-based DT, demonstrate the relevance and potential of these technologies.

The integration of DTs has created immersive experiences that bridge the gap between the

physical and digital worlds, allowing users to visualize and manipulate robotic systems remotely more effectively [4]. This is further supported by the work of [5] who proposes an immersive digital twin applied to a Manufacturing Execution System for monitoring and controlling industry 4.0 processes, integrating various technologies including augmented (AR) and virtual (VR) realities. [6] also emphasizes the importance of incorporating other Industry 4.0 technologies, such as system integration, connectivity with industrial protocols, and cloud services, alongside AR/VR for developing digital twins in industrial environments.

The foundational aspects of Digital Twins, including their communication protocols and architectural considerations, are crucial for effective implementation in industrial settings, as explored by [7] in their study of Digital Twin and its communication protocol in factory automation cells.

A comprehensive understanding of DT technology, its applications, capabilities, and challenges within the built environment, as reviewed by [8], provides a broader context for their transformative potential, highlighting their role in enhancing operational efficiency and predictive maintenance while also addressing integration and data consistency challenges.

This project aims to develop a 3D environment for Digital Twins in an Advanced Manufacturing

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Didactic Plant. The focus will be on creating a digital model that not only represents the physical environment but also facilitates the simulation of real-world scenarios, operator training, and process optimization, adding the possibility to be smoothly integrated within the Plant's infrastructure (Figure 1), for its system includes robotic arms for material handling, followed by various stations for inspection, drilling, and cleaning, these components are interconnected and controlled by a network of PLCs, with a Supervisory Control and Data Acquisition (SCADA) system providing a central interface for monitoring and controlling the entire plant, gathering real-time data from sensors and machines. The steps of 3D data capture, modeling, and information integration are addressed (Figure 2), with the goal of overcoming the inherent complexity challenges in existing industrial environments.

The research will contribute to the advancement of knowledge in the application of DTs in educational and industrial contexts, preparing future professionals for the challenges of advanced manufacturing.

Materials and Methods

The method adopted for the development of the Digital Twin environment in the Advanced Manufacturing Didactic Plant followed a qualitative approach, grounded in best practices and tools identified through extensive literature analysis, case studies, and expert consultations. This approach was crucial for gaining an in-depth understanding of the complexities involved in creating a functional and immersive 3D environment for a Digital Twin. The initial research phase focused on identifying and evaluating various software solutions available in the market, considering not only their technical capabilities but also practical factors such as development time, team learning curve, and financial implications associated with software licenses. Collaboration with plant personnel was a crucial element in this and the next phase, providing valuable insights into operational requirements and the specificities of the existing infrastructure, especially regarding connectivity with the plant's PLCs. The software selection criteria were multifaceted, aiming to find

Figure 1. Plant's structure diagram.

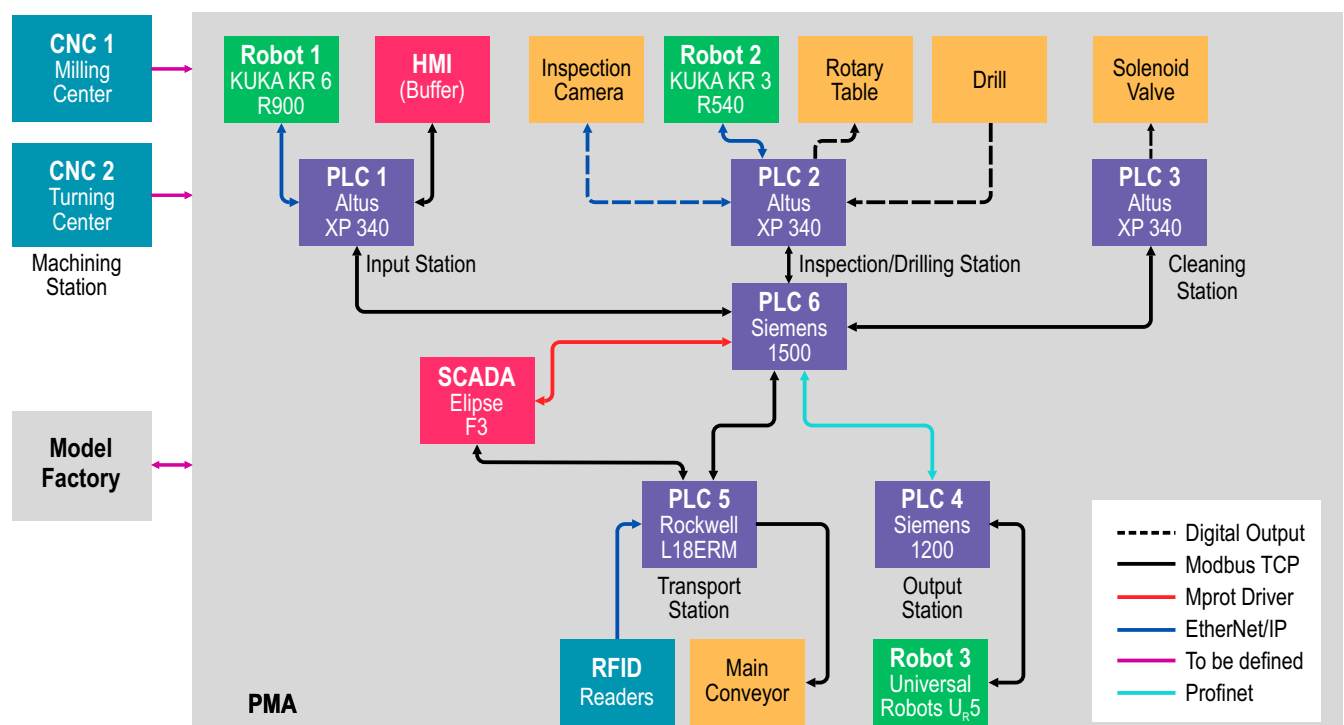
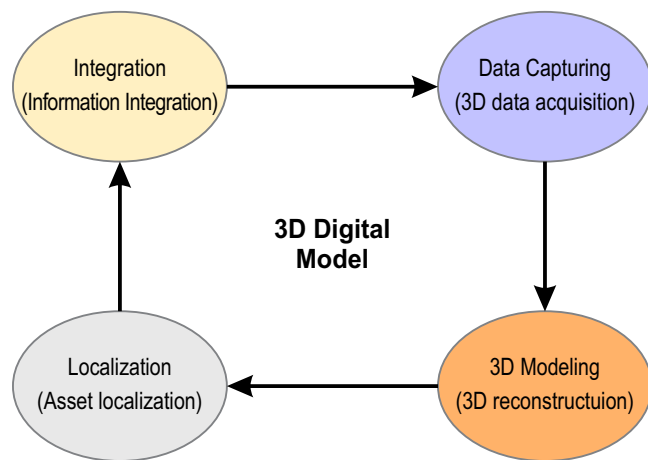


Figure 2. Proposed workflow to create a digital model for existing industrial environments.



a solution that offered an optimal balance between functionality, usability, and cost-effectiveness.

Platforms with robust 3D modeling, emulation, and simulation capabilities were evaluated, as well as the ability to integrate with industrial control systems. Interoperability was a key factor, given the need for fluid communication between the virtual 3D environment and the physical PLCs. The scalability of the solution was considered, ensuring that the environment could be expanded and adapted for future needs of the didactic plant.

The initial research phase, which spanned the first few months of the project, was intensive and comprehensive, involving literature analysis, case studies, and consultation with experts. This period was fundamental for building a solid knowledge base on Digital Twins and the nuances of 3D modeling and emulation, allowing the team to make informed decisions about the tools and approaches to be used.

Following the initial research, the subsequent phase focused on the meticulous development of the operational environment within the selected software. This process involved creating precise 3D models of the plant's equipment and infrastructure, configuring simulation parameters, and implementing control logics. Concurrently, significant efforts are made to establish seamless connectivity with the PLCs. To overcome the inherent difficulties of integrating diverse communication protocols (e.g., Siemens S7, Allen-Bradley Ethernet/IP, Modbus TCP), a

multi-strategy approach was employed. A dedicated industrial communication OPC UA server has been included to act as a standardized middleware, translating proprietary PLC protocols into a common language for the digital twin software, developing custom driver scripts where necessary for legacy systems and implementing robust error-handling and data buffering routines to ensure stability during network latency or interruption. This step is necessary for real-time data acquisition and for accurate monitoring and analysis of plant performance. The successful integration of PLC data with the 3D environment allows the digital twin to reflect the plant's current state with high fidelity, enabling early detection of anomalies, process optimization, and applications, such as predictive maintenance.

The validation of the digital twin's accuracy and performance was conducted against a stringent set of criteria throughout the development cycle. This validation strategy included a verification that every virtual asset correctly mimicked the behavior of its physical counterpart (e.g., motor start/stop, sensor state changes) through scripted test scenarios.

A comparison of time-synchronized data logs from the physical PLCs with the data received and visualized in the digital twin enabled to quantify latency and ensure data accuracy, that exceeded a threshold of 99.5%z subjecting the system to high-frequency data exchange and simulated network failures to evaluate the robustness of the OPC UA. It was also stressed communication and the effectiveness of the error-handling routines, having plant operators and control engineers interact with the digital twin to provide qualitative feedback on the realism and usability of the environment for its intended didactic and operational purposes. The complexity of this integration lies in the diversity of communication protocols and the need to ensure data synchronization between the physical and virtual systems.

Results and Discussion

The development of the environment within these chosen platforms is currently ongoing, with

an example being presented to visitors interested in the process (e.g. Figure 3).

A critical step was the selection of software tools. After evaluation, Rockwell Automation's Emulate 3D was chosen for simulation and emulation [9], while SolidWorks was selected for high-fidelity 3D modeling [10]. This bifurcated approach aligns with common industry practice but presents a notable integration challenge. Unlike unified platforms, which offer native CAD and control simulation integration, our chosen stack requires a robust data bridge between the separate modeling and simulation environments. While this approach offers flexibility in using best-in-class tools, it introduces potential complexity in maintaining model synchronization. The success of this architecture hinges on the stability of the communication layer, which became the next significant challenge.

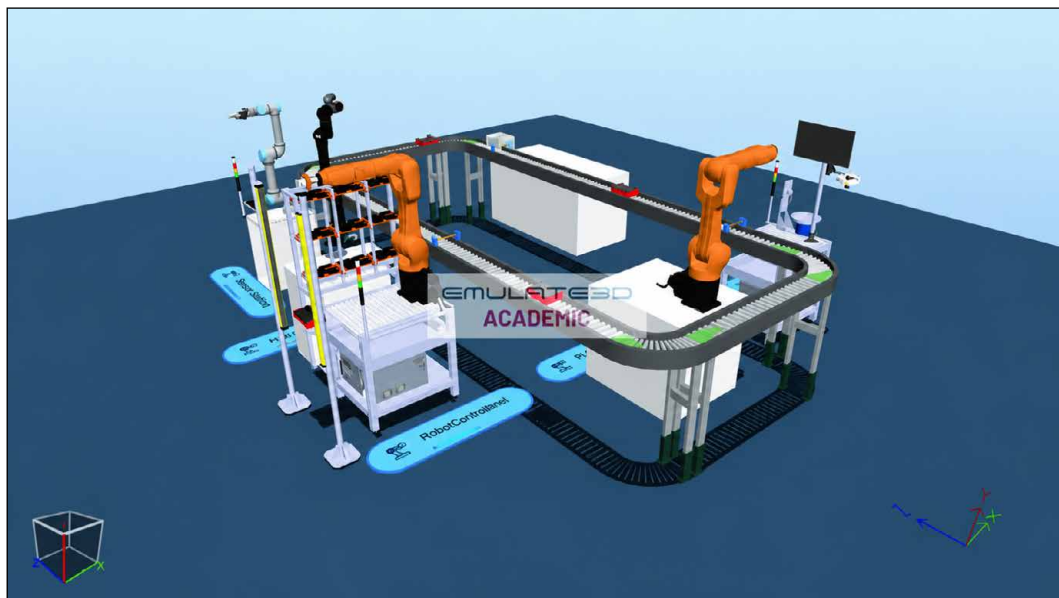
The initial communication architecture proposed a dual-protocol strategy using Ethernet/IP and OPC UA to facilitate comprehensive data collection from the plant's programmable logic controllers (PLCs). However, practical integration issues with the legacy PLCs prevented a stable Ethernet/IP connection. Consequently, the architecture was adapted to utilize OPC UA as the sole protocol

for the main PLC, centralizing all data acquisition (Figure 4). This shift provide more reliable and secure data aggregation than attempting to manage multiple, complex protocol translations, even if it temporarily limits the scope of connected devices.

Within Emulate 3D, data acquisition is managed through a dedicated communication browser that establishes a one-to-one mapping between virtual "tags" in the simulation and their physical counterparts in the PLC (Figure 5). This method ensures real-time data reflection with minimal latency. While highly effective for emulation, this tight coupling can be a limitation for broader DT applications. Unlike a more abstracted data layer, such as a historical database or a cloud-based IoT hub, this direct tag-based system is less suited for long-term trend analysis and machine learning applications. For the current phase focused on control logic validation and operator training, however, its performance and simplicity are optimal.

The ongoing development of this 3D DT is poised to deliver significant benefits in training, optimization, and safety. The move towards an immersive 3D interface, as opposed to the 2D schematics common in traditional SCADA systems, offers an intuitive method for personnel to understand complex processes. Furthermore, the ability to

Figure 3. Current plant 3D environment.



simulate and analyze manufacturing processes without disrupting physical operations provides a vital sandbox for validation and optimization. By integrating real-time sensor data via OPC UA, the model transitions from a static simulation to a live DT, enabling predictive maintenance and rapid troubleshooting. The future success of the project will depend on effectively scaling the data architecture beyond emulation to support plant-wide data analytics while managing the inherent complexity of the multi-software environment.

Conclusion

This project embarked on the endeavor of developing a 3D environment for Digital Twins within an Advanced Manufacturing Didactic Plant. The methodology adopted emphasized a thorough research phase to understand the nuances of Digital Twins and 3D modeling/emulation, followed by the practical development of the environment and efforts to integrate with the plant's PLCs. The selection of Rockwell Emulate 3D for simulation and emulation, and Solidworks for 3D modeling, represents a strategic choice aimed at leveraging industry-standard tools for this complex undertaking, exceeding its original objectives and assignments.

Significant progress has been made in developing the 3D environment; however, integrating with the plant's PLCs remains a challenge due to hardware issues that complicate bridging virtual simulations and real-world industrial processes. Addressing these hardware impediments is essential to achieve full integration and unlock the Digital Twin's potential for real-time monitoring, analysis, and optimization within the didactic plant. Overcoming these challenges will enable a dynamic, interactive digital representation that supports advanced simulation, training, and predictive maintenance.

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