Real-Time Virtual Reality Visualization and Control for Digital Twin Applications in Industry 4.0

Ahmet Demirbas[1] and Wenyao Xu[#]

[1]Williamsville East High School, USA
[#]Advisor

ABSTRACT

The Fourth Industrial Revolution (Industry 4.0) aims to transform manufacturing processes through the use of technologies like the internet of things, cyber-physical systems, and artificial intelligence. Digital twins -virtual replicas of physical systems- emerged as powerful tools for monitoring, optimizing, and controlling Industry 4.0 operations. This paper explores applying virtual reality (VR) technology for real-time visualization and control of digital twin applications in Industry 4.0 cyber manufacturing environments. I present the development and implementation of a VR twin environment for interacting and controlling of a 3D printer. The system features a custom Unity 3D software architecture with VR libraries, providing a realistic low-latency experience for navigating and visualizing real-time data such as pressure charts, live video feeds, and position data of 3D printer head. It also enables interacting with physical machines via their virtual counterparts, such as using a virtual on-off switch for the 3D printer. Through evaluation of hardware selection and software design decisions, the paper contributes novel insights into the use of VR twins in Industry 4.0 applications. It also explores integration of generative AI with the VR twin, which opens novel research directions for predictive simulations, what-if analyses, and intelligent decision support systems.

Introduction

The world has gone through three major industrial revolutions. The first industrial revolution (18th century) substituted manual labor with mechanized production using steam powered machines. The second industrial revolution (early 20th century) was driven by electricity and led to improved efficiency via the use of semi-automated production lines. The third industrial revolution (late 20th century) was enabled by the development of digital technologies and the internet and gave rise to a digitally connected world and globalization of economies.

We are now in the midst of the fourth industrial revolution, Industry 4.0 (Dalenogare et al. 2018; Thames et al. 2017), which arose from the confluence of many technologies including the internet of things (IoT), cyber-physical systems (CPS), additive manufacturing (i.e., 3D Printing), robotics, cloud computing, big data analytics, artificial intelligence (AI), machine learning (ML), augmented reality (AR), and virtual reality (VR). Industry 4.0 enables real-time data exchange, remote monitoring, data-driven decision making, rapid prototyping, and on-demand product customization.

Several challenges remain for realizing the Industry 4.0 vision. Many manufacturing facilities still use siloed control systems and devices communicating through incompatible protocols. Often there is no efficient strategy for optimizing industrial processes due to the long timelines required for physical deployment and testing.

Digital twins play a key role in overcoming these challenges (Javaid et al. 2023; Van der Valk et al. 2020). A digital twin is a virtual replica of a physical system, such as a factory floor. By modeling existing machinery and equipping them with sensors, businesses can create virtual twins of them for analysis and testing.

Such digital twins allow teams to visualize 3D models and data in real-time remotely and enable data-driven decision making. They allow exploration of alternate designs to optimize industrial processes virtually, which accelerates process optimization and innovation.

VR applications, combined with digital twins and metaverse technology (Mystakidis 2022), enable natural visualization, interaction, and even control of the physical counterpart. VR provides users with a sense of 3D immersive localization and mapping within the virtual environment. In hazardous environments like smelting, chemical, and nuclear factories, VR headsets and associated hand/touch controllers allow remote control of the machines and robotic arms, protecting human operators from dangerous conditions.

Figure 1. An example of digital twin view from my project.

Furthermore, VR digital twins enable the creation of shared virtual spaces for remote experts to collaborate in real-time. This supports data-driven decision-making through interactive visualizations of real-time data collected from multiple sources. Last but not least, VR also enables immersive training playgrounds that replicate real-world environments.

Contributions of this Paper

This paper explores the application of VR technology in the context of Industry 4.0, and more specifically in the context of real-time visualization and control of digital twin applications. While there has been significant work on digital twins, and ample work on VR, the intersection of both areas remains relatively unexplored, and presents opportunities for innovative solutions.

I performed this work as part of a prototype project to enable real-time monitoring and control of a Creality Ender-3 Pro 3D printer located at the University XXX's [1]North Campus. The other team members looked at integrating a mechanical sensor/actuator interface to the 3D printer for linking it to the digital twin

[1] Removed for double blind review

and developed a web-based digital twin. My work was on creating a digital twin in the VR environment to provide an enhanced interactive experience with improved information visualization and intuitive control.

Section 4 of this paper presents the hardware (Quest 2 headset) and software (customized Unity 3D framework and VR libraries) components and discusses the capabilities they provide and the rationale behind their selection. The evaluation and selection of these hardware components, as well as the design decisions in developing the software architecture, contribute novel insights. Section 5 showcases the realized VR twin environment illustrated with screenshots and discusses personal experience using the system. This practical implementation serves as a valuable reference for future work in VR twin applications. Section 6 discusses the potential of supporting the VR twin with generative AI and outlines several novel research directions in order to enrich digital twin applications in Industry 4.0.

Related Work

Industry 4.0 has drawn significant attention from both researchers and practitioners (Dalenogare et al. 2018; Javaid et al. 2023). Many studies have investigated the potential benefits and challenges of Industry 4.0, as well as how it would impact different sectors and industries (Thames et al. 2017). Moreover, there has been a lot of work on industry 4.0 exploring its various aspects, including smart manufacturing, CPS, IoT, cloud computing, and AI (Jagatheesaperumal et al. 2021; Pivoto et al. 2021).

The use of VR technology has also been explored across diverse domains, including gaming, education, healthcare, and entertainment (Voštinár et al. 2021). Additionally, VR has been employed in various industrial contexts, such as training simulations, product design and visualization, and remote collaboration (Naranjo et al. 2020).

However, the application of VR technology in the context of Industry 4.0, and more specifically for real-time visualization and control of digital twin applications, remains a relatively unexplored area (Van der Valk et al. 2020). The intersection of VR and digital twins presents unique challenges and opportunities.

My work aims to bridge the gap between the current modus operandi and the Industry 4.0 vision, by providing an experience report on developing a real-time VR visualization and control system for a digital twin application.

System Description

I performed this work as part of a prototype project at the University XXX[2], to enable real-time monitoring and control of a Creality Ender-3 Pro 3D printer located at the university's North Campus. While the other team members developed mechanical sensor/actuator interface to the 3D printer for linking it to the digital twin, my research explored creating the digital twin in the VR environment for an enhanced interactive experience. Therefore, this paper gives only a brief overview of the mechanical sensor/actuator interface on the physical twin, and instead presents the VR headset hardware and VR software components in detail.

[2] Removed for double blind review.

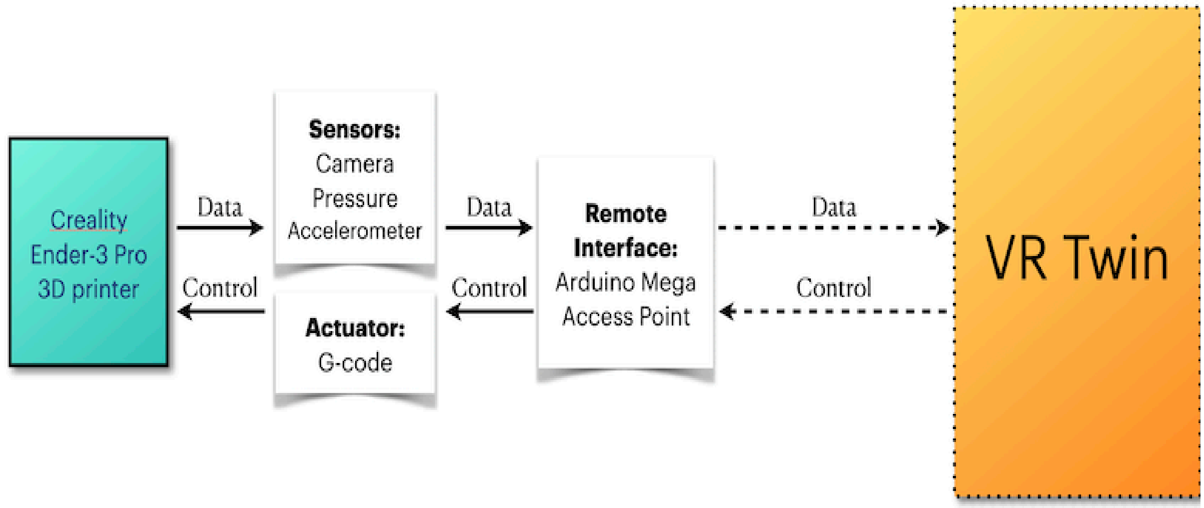

Figure 2. The physical plant architecture.

Hardware Components

Hardware in the Physical Plant

Figure 2 shows the architecture of the physical plant. The project utilized a Creality Ender-3 Pro 3D printer. To track printer vibrations, an MPU6050 inertial measurement unit was integrated. A pressure sensor was placed between the linear stage and the syringe plunger to monitor pressure changes. A camera was mounted on the printer bed to capture the printing process, while another camera was positioned outside the printer to monitor the entire system.

The actuation/control of the 3D printer was achieved by sending Marlin G-code commands to an SKR Mini E3 V2.0 board, which replaced the original printer board. An Arduino MEGA was responsible for reading data from the sensors and performing local processing. When requested by the access point, the Arduino sends available sensor data over the UART to the ESP32 microcontroller with the integrated WiFi, which transmits it over the network.

The Quest 2 VR Headset

The Quest 2 VR headset from Meta possesses top tier hardware specifications to provide a smooth VR experience. With a price-point as low as $200 as of 2024, it stands out among competition as the cost-effective option. Other reasons to favor Quest 2 include its wireless headset operation and the large ecosystem Meta provides around it through its Metaverse initiative. Here is a detailed description of the headset specifications.

The Quest 2 headset's dual displays offer 1832x1920 pixel resolution per eye with a refresh rate up to 120 Hz for ensuring smooth and fluid visuals. The three-position interpupillary distance (IPD) adjustment allows users to tailor the lens position for optimal clarity. The headset's inside-out tracking system utilizes four built-in cameras to provide six degrees of freedom (6DOF) for both head and hand tracking. This innovative approach obviates the need for external sensors and enables users to explore virtual worlds with unrestricted freedom and mobility.

The headset is powered by the Qualcomm Snapdragon XR2 chipset and is complemented by 6GB of RAM. Its storage options range from 64GB to 256GB to support content libraries and user needs. The headset supports 2-3 hours of playtime on a full charge. Quest 2 runs on Meta's bespoke Android-based operating system, which is optimized for providing immersive virtual reality experiences over the Snapdragon chipset.

The Oculus Touch controllers are worn on user's hands to enhance the VR interaction experience. They have good ergonomics that enable the user to navigate VR environments and manipulate virtual objects with haptic feedback.

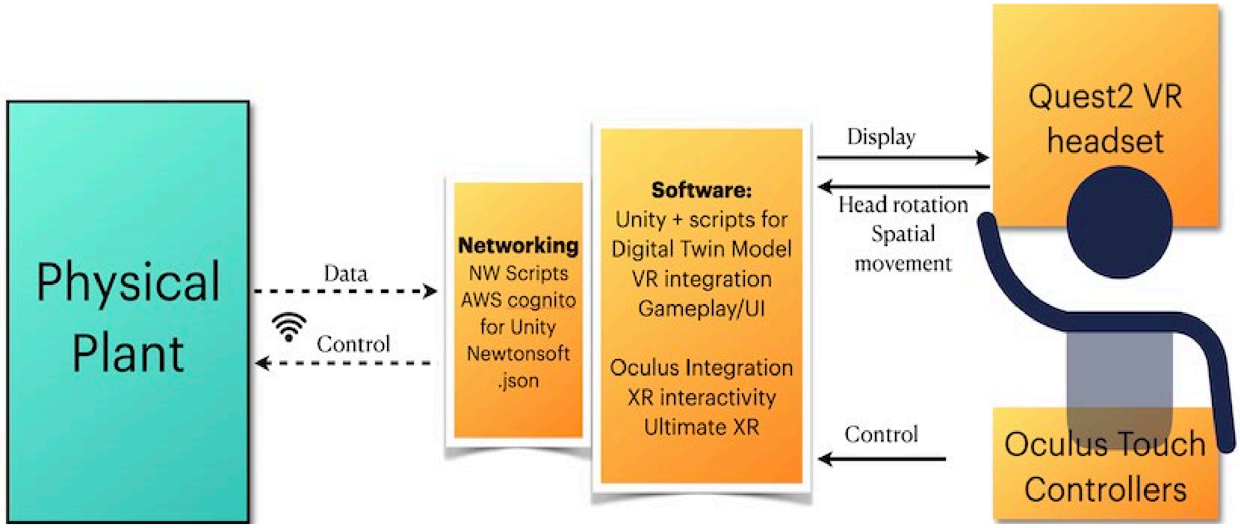

Figure 3. The VR twin architecture.

Software Components

Figure 3 illustrates the architecture of the VR twin environment. I chose Unity 3D as the development platform for the project for its flexibility and its extensive VR library and package ecosystem (Messaoudi et al. 2015). With Unity, it is possible to develop cross-platform VR applications, including the Oculus Rift and HTC Vive headsets, without needing a significant rewrite. Unity's asset store and its community resources help in accelerating the development process.

Unity offers strong VR support through its XR Interaction Toolkit and through third-party libraries, such as Oculus Integration, SteamVR, and UltimateXR. These libraries provide pre-built components for VR development in order to simplify VR interactions. To glue these packages together and build the VR twin, I developed several scripts. I developed the codebase in C# programming language using Unity Version 2021.3.0f1. The below section covers the essential libraries and frameworks I utilized and provides an overview of the codebase by describing the main scripts.

Scripts Developed

I developed the following categories of custom scripts to build the VR twin.

The Utility Scripts managed WebSocket connections, data collection, and printer position tracking. The CollectData script was responsible for sending UnityWebRequests to initiate connections with the website server. The GetData script (230 lines of code) managed connections by obtaining an access token using the authentication credentials retrieved from Amazon Cognito, opening a WebSocket connection to a specified URL, and subscribing to the events to receive updates. It processed incoming data and extracted pressure sensor values and extracted positional coordinates to track the printer head's position. It also ensured proper cleanup by unsubscribing from events when the user quit the application. The PrinterPos script tracked the positions of the 3D printer's head/nozzle. It scales the Vector3 input given as (x,y,z) data to fit the printer's coordinate system, and uses this to update the target positions within the VR twin.

The VR Interaction Scripts managed the user's virtual experience. The UxrGrabPointShapeAxisAngle script allowed users to grab and manipulate objects in VR. The TeleportationProvider.cs script (420 lines of code) enabled players to teleport within the VR environment to facilitate navigation without having to move large distances in the real world.

The Gameplay Scripts managed player interactions and controls. The UxrAvatar.cs script (1200 lines of code) managed VR player movements and interactions with the virtual objects.

Finally, the UI Scripts managed the user interface. The MainMenu.cs script handled the main menu for providing an entry point to the virtual experience. The UxrCanvas script (320 lines of code) managed the VR heads-up display (HUD) and various object UI elements.

Networking Software

The VR twin uses networking to monitor the physical plant and send back instructions to control it. The NewtonSoft.Json Unity package was used for sending and receiving data in JSON format over the network. This package simplified creating, parsing, and querying data structures as JSON objects. The JSON data format was preferred since it provides standardizing communication and allows extending the system in the future.

The AWS Cognito for Unity package is used for securing user authentication and access control mechanisms. By leveraging Amazon Cognito's authentication services, we ensure that only authorized users can access and interact with the digital twin.

Unity Packages and External Libraries

The project comprises of the following Unity packages and external libraries.

The Oculus Integration library was necessary for developing VR applications for the Oculus headsets, including the Quest 2. This library provided software development kits and assets designed for Oculus devices and supported hand tracking features. OVRManager, OVRInput, and OVRCameraRig components were used to manage Oculus VR headset settings, handle input from Oculus Touch controllers, and configure the camera setup, respectively.

Another essential component was the XR Interaction Toolkit, which implemented common VR interactions such as grabbing, interacting with the UI elements, and teleporting. The XR Controller component managed input from VR controllers, while the XR Grab Interactable component allowed objects to be grabbed within the virtual environment. To enhance the overall VR experience, the project also incorporated UltimateXR. This library brought in advanced interaction models and support for locomotion systems and avatar management.

Results

In this section, I describe the VR twin environment realized in the project.

The main menu serves as the entry point of the application, where users can start the experience and adjust settings. It includes a map of factory locations for the user to select.

Once a location is chosen, the user is transported to a virtual factory space featuring the machine visualizations. This is the primary environment where VR interactions occur. It features a 3D model recreation of the 3D printer table and enables the users to interact with various tools using easy clip-on VR objects. The scene includes a data chart displaying real-time pressure data, a full 3D model of the real-time model of the 3D printer, and an interactive screen showcasing a live video feed of the 3D printer.

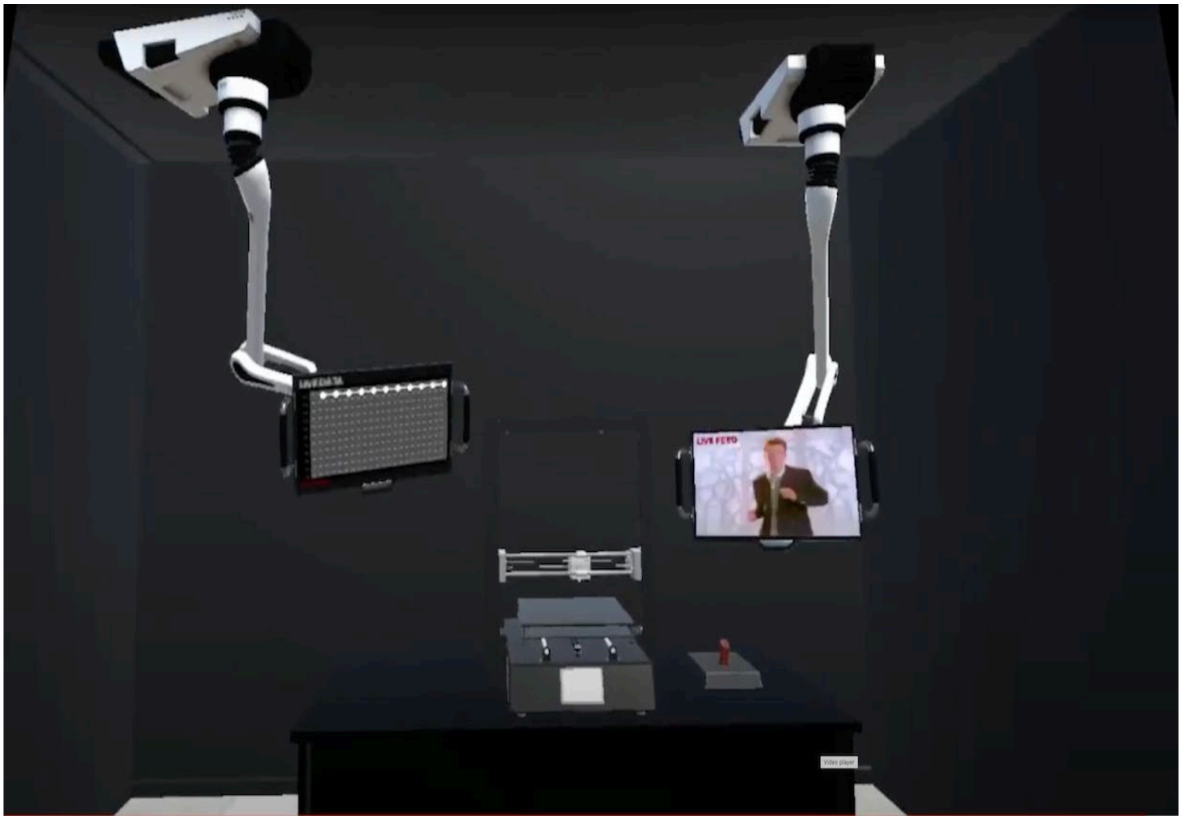

Figure 4. The VR scene displaying the 3D-printer, sensor data display, and video monitor.

Pressure data is received as JSON packages from the WebSocket server and is visualized through an updating chart. The video rendering of the live printer video feed is received as Base64 frame data from the main WebSocket server and converted to images to be rendered on the screen. In our deployment, a dummy video feed using a Rick Astley music clip was implemented to showcase the video rendering capability in the VR environment.

Figure 5. The VR scene displaying the lab sensor data display.

The printer head position data is a crucial aspect for the fidelity of the digital twin. As described earlier, this data is retrieved from the physical printer and sent over the network to the VR twin. The PrinterPos script tracks the head position data and updates this in the VR visualization.

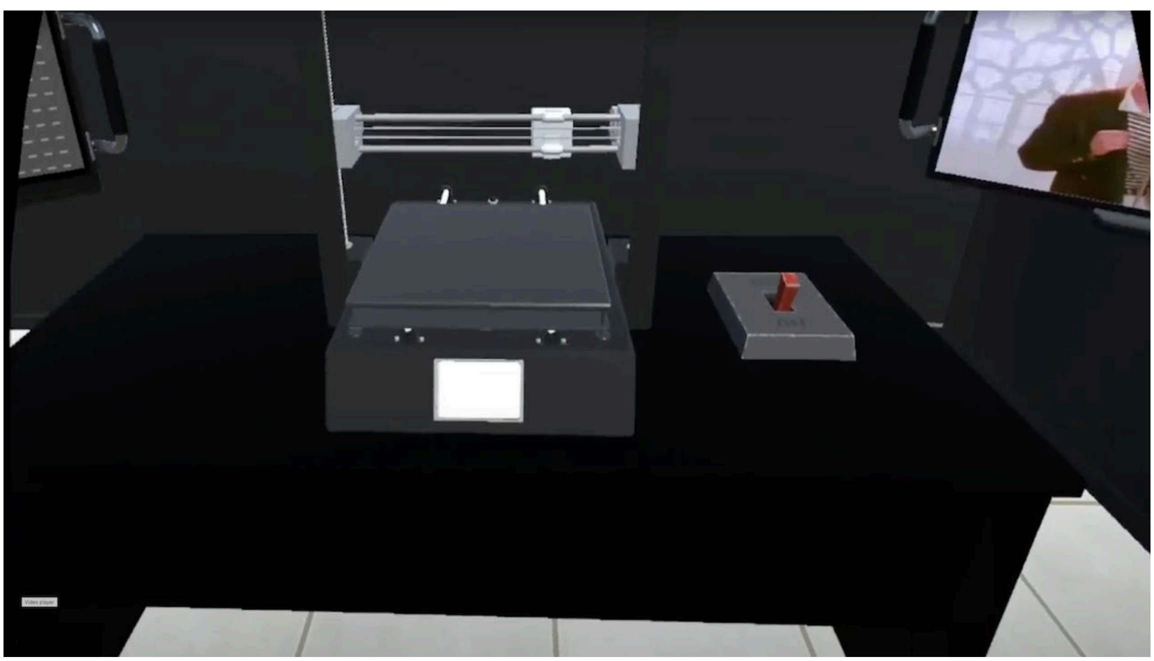

Figure 6. The VR scene displaying the 3D printer head and the virtual on-off switch.

For controlling the physical device from the VR twin, I implemented a virtual on-off switch as shown in Figure 6. The VR client sends the trigger event of this switch over the network to the physical plant. On the physical plant, this command is sent over to the printer server using G-code terminal, enabling a VR user to turn on and off the printer.

Thanks to the Quest 2 headset and Unity packages employed, and custom scripts developed, the VR twin provides a low-latency realistic interaction experience. The interaction is smooth and does not contain jitters. To the user, the VR twin provides an immersive 3D environment to interact with the machinery.

Future Work: Augmenting VR Twin with gGnerative AI

Generative AI can play a major role in enabling next generation VR twin applications in Industry 4.0 settings. In future work, through the use of generative AI, VR twin applications can be enhanced by the following capabilities as listed in order of feasibility and impact.

Firstly, generative AI models trained on computer-aided-design (CAD) drawings can automatically generate 3D representations of the machinery and factory floor. This can reduce the time and effort required for manual modeling and accelerate digital twin creation.

Secondly, natural language processing (NLP) models can be employed to interpret spoken commands to enable conversational interactions with the digital twin, through which the physical plant can be affected. Furthermore, gesture recognition can enable more natural interactions within the VR environment.

Thirdly, techniques like neural radiance fields (NeRF) can create photorealistic 3D environments within the VR twins. AI models can optimize scenes based on the point of view and optimize the use of computing resources.

Finally, integrating generative AI with simulation tools within the VR twin can enable predicting outcomes of certain manufacturing scenarios and process changes. This can be used to generate simulations for what-if analysis and process optimization. These what-if scenario simulations within the VR twin, allowing the user to test and implement them virtually before applying them in the physical plant.

Conclusion

Applying VR technology in the context of Industry 4.0 digital twin environments enables real-time 3D immersive visualization, interaction, and control. My work explored the proof-of-concept development and deployment of a VR twin and demonstrated its potential to improve industrial processes. The VR twin I developed leverages the immersive VR capabilities and enables users to interact with the machines in an intuitive fashion. The selection of Quest 2 headset and the design of a custom software architecture built on the Unity 3D framework played a major role in achieving a realistic and interactive user experience. The evaluation and selection of these hardware components and the software architecture design decisions contribute novel insights to the field of VR twin applications. In future work, integrating generative AI tools within the VR twin would open exciting new research directions. In particular, augmenting VR twins with generative AI can enable predictive simulations, what-if analyses, and intelligent decision support systems for Industry 4.0 applications.

Acknowledgments

I would like to thank my advisor for the valuable insight provided to me on this topic.

References

Dalenogare, L. S., Benitez, G. B., Ayala, N. F., & Frank, A. G. (2018). The expected contribution of Industry 4.0 technologies for industrial performance. International Journal of production economics, 204, 383-394.

Jagatheesaperumal, S. K., Rahouti, M., Ahmad, K., Al-Fuqaha, A., & Guizani, M. (2021). The duo of artificial intelligence and big data for industry 4.0: Applications, techniques, challenges, and future research directions. IEEE Internet of Things Journal, 9(15), 12861-12885.

Javaid, M., Haleem, A., & Suman, R. (2023). Digital twin applications toward industry 4.0: A review. Cognitive Robotics, 3, 71-92.

Messaoudi, F., Simon, G., & Ksentini, A. (2015, December). Dissecting games engines: The case of Unity3D. In 2015 international workshop on network and systems support for games (NetGames) (pp. 1-6). IEEE.

Mystakidis, S. (2022). Metaverse. Encyclopedia, 2(1), 486-497.

Naranjo, J. E., Sanchez, D. G., Robalino-Lopez, A., Robalino-Lopez, P., Alarcon-Ortiz, A., & Garcia, M. V. (2020). A scoping review on virtual reality-based industrial training. Applied Sciences, 10(22), 8224.

Pivoto, D. G., de Almeida, L. F., da Rosa Righi, R., Rodrigues, J. J., Lugli, A. B., & Alberti, A. M. (2021). Cyber-physical systems architectures for industrial internet of things applications in Industry 4.0: A literature review. Journal of manufacturing systems, 58, 176-192.

Thames, L., & Schaefer, D. (2017). Industry 4.0: an overview of key benefits, technologies, and challenges. Cybersecurity for Industry 4.0: Analysis for Design and Manufacturing, 1-33.

Van der Valk, H., Haße, H., Möller, F., Arbter, M., Henning, J. L., & Otto, B. (2020, August). A Taxonomy of Digital Twins. In AMCIS.

Voštinár, P., Horváthová, D., Mitter, M., & Bako, M. (2021). The look at the various uses of VR. Open Computer Science, 11(1), 241-250.