Department of Mechanical Engineering

Industrial Metaverse: Revolutionizing Industry 5.0 with Digital Twins and Extended Reality

Xinyi Tu

Aalto University

DOCTORAL THESES

Aalto University publication series
DOCTORAL THESES 171/2024

Industrial Metaverse: Revolutionizing Industry 5.0 with Digital Twins and Extended Reality

Xinyi Tu

A doctoral thesis completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Engineering, at a public examination held at the K1 (Otakaari 4) Lecture Hall 216 of the school on 13 September 2024 at 12:00.

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Aalto University publication series
DOCTORAL THESES 171/2024

ISBN 978-952-64-1978-7 (printed)
ISBN 978-952-64-1979-4 (pdf)
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)
http://urn.fi/URN:ISBN:978-952-64-1979-4

Unigrafia Oy
Helsinki 2024

Finland

NORDIC SWAN ECOLABEL
Printed matter
4041-0619

A! Aalto University

Abstract

Aalto University, P.O. Box 11000, FI-00076 Aalto www.aalto.fi

Author
Xinyi Tu

Name of the doctoral thesis
Industrial Metaverse: Revolutionizing Industry 5.0 with Digital Twins and Extended Reality

Publisher School of Engineering

Unit Department of Mechanical Engineering

Series Aalto University publication series DOCTORAL THESES 171/2024

Field of research Mechatronics

Manuscript submitted 17 May 2024 **Date of the defence** 13 September 2024

Permission for public defence granted (date) 18 June 2024 **Language** English

☐ **Monograph** ☒ **Article thesis** ☐ **Essay thesis**

Abstract
The industrial sector is experiencing a paradigm shift to Industry 5.0, which emphasizes the integration of human ingenuity and advanced technologies. Central to this transformation is the convergence of digital twins and extended reality (XR), which together foster a more human-centric, technology-augmented industrial ecosystem. The dissertation looks into these transformative technologies within the context of the industrial metaverse, addressing the challenges that have impeded the convergence of digital and physical spaces in industrial settings.

Foremost among these challenges is the limitation of current industrial XR solutions, which lack dynamic data interaction with digital twins and robust evaluation of control accuracy. This work addresses this gap by developing a mixed reality interface that actively interacts with a digital twin-based industrial crane, accompanied by measurement protocols for accessing the application's control accuracy. This application serves as a practical entry point into the industrial metaverse, illustrating how digital and physical elements can be synchronized for enhanced operation.

Expanding on this foundation, the thesis tackles the scarcity of systematic integration of XR and digital twins across varied industrial machinery and environmental settings. By introducing the TwinXR method and implementing it on two case studies, the work enables scalable, efficient XR application development that leverages digital twin descriptions for enhanced information management and system interoperation across diverse industrial settings.

Finally, the research proposes a comprehensive architecture of the industrial metaverse that extends beyond prevailing consumer-centric architectures and their narrow focus on XR. This architecture integrates physical factories with the metaverse through data flow and knowledge synchronization facilitated by the interplay of digital twins and semantic models. A case study on in-plant material flow tracking illustrates the practical application and benefits of this architecture in meeting the complex demands of industrial systems.

Overall, the dissertation provides a thorough exploration of the industrial metaverse, traversing from focused applications to broader integration methodology, culminating in an expansive architectural design. The findings highlight the transformative impact of the industrial metaverse in the Industry 5.0 context, where digital twins and XR consolidate to reshape industrial processes and enhancing human-machine collaboration.

Keywords Industrial Metaverse, Digital Twins, Extended Reality, Human-Machine Interaction, Cyber-Manufacturing, Industry 5.0

ISBN (printed) 978-952-64-1978-7 **ISBN (pdf)** 978-952-64-1979-4

ISSN (printed) 1799-4934 **ISSN (pdf)** 1799-4942

Location of publisher Helsinki **Location of printing** Helsinki **Year** 2024

Pages 143 **urn** http://urn.fi/URN:ISBN:978-952-64-1979-4

Preface

My journey into the “metaverse” began amidst the dawn of Industry 4.0, when the term was barely recognised outside the science fiction Snow Crash. It was during this pioneering phase that I first engaged with the two core metaverse technologies: digital twins and extended reality (XR). My initial explosure occurred during an internship at Siemens PLM Software in Shanghai in 2016, where I modelled digital twins of industrial processes. This experience led to my bachelor’s thesis at Siemens Digital Factory in Nuremberg in 2017, where I developed an API bridging Siemens software running digital twins with the game engine Unity enabling XR development. These formative experiences sparked an immediate connection when I encountered the demonstration of digital twin research during my exchange studies at Aalto University in 2019, which led to my master’s thesis at Aalto Industrial Internet Campus. This opportunity allowed me to delve deeper into digital twins and XR, and proceed with my doctoral studies. My doctoral research started from a practical entry point, developing an XR application for a digital twin-based system, and evolved into to a systematic approach for integrating these technologies. This period of research coincided with the European Union’s strong push towards Industry 5.0, emphasizing a human-centric, sustainable, and resilient future of industry, which infuses my research with fresh inspiration and motivation. Consequently, the thesis culminates in a comprehensive architecture for the industrial metaverse, envisioning a cohesive and interconnected system seamlessly interfacing human and industrial elements.

To this end, I would like to express my gratitude to everyone who has supported my doctoral journey. My sincere thanks to my thesis supervisor Prof. Kari Tammi for his invaluable guidance, trust, and encouragement. I also deeply appreciate Prof. Tauno Otto from Tallinn University of Technology and Dr. Yuqian Lu from University of Auckland for pre-examining this thesis, and Tauno for acting as the opponent for my defence. Special thanks our DigiTwin Lab: Dr. Juuso Autiosalo for introducing me to the team and guiding my early research; Dr. Riku Ala-Laurinaho for advising my thesis and leadership of the lab; Chao Yang for our productive

collaboration and management of our NECOVERSE project; Our former colleague Dr. Pauli Salminen for his support in our MACHINAIDE project; Joel Mattila for his tech expertise. I also value many more brilliant minds at our Mechatronics group, whose insights and enthusiasm enriched our research. In addition, I want to thank my collaborators for their essential contributions to our cross-field and interdisciplinary research: Nassim Sehad for telecommunication expertise, Bruna De Castro e Silva for her insights into technology law, and Matteo Zallio for his guidance in ethical design. Their diverse perspectives have greatly enriched my research and amplified its significance.

I extend my thanks to the MACHINAIDE and NECOVERSE consortia members, along with our academic and industrial partners, for their exceptional collaboration on these co-innovation projects. Their support provided the practical context crucial in expanding and validating my research impact. I am also grateful to Business Finland, the Aalto University Doctoral Programme for funding, and the Neles Oy 30 Years Foundation for their encouragement grant. Furthermore, my participating in several pioneering Industry 5.0 and metaverse initiatives, including the FORGING Expert Forum, Metavethics Institute, and Metaverse Standards Forum, has provided me with valuable insights and inspiration.

At the final stage of my doctoral journey, I had the privilege of a six-month research visit to University of Cambridge 's Institute for Manufacturing, Cyber-Human Lab, renown its work in augumenting human capabilities with technologies, particularly within the metaverse domain. I am grateful to Dr. Thomas Bohné and Dr. Sławomir Tadeja for hosting me and providing invaluable guidance. Our collaboration on XR-based manual assembly research has broadened my research landscape, integrating human factors crucial for advancing Industry 5.0.

Finally, I want to express my heartfelt thanks to my friends and family, especially my mother, father, and grandfather, as well as my beloved Perttu, for everything.

So long, and thanks for all the fish.

Helsinki, August 13, 2024,

Xinyi Tu

Contents

List of Publications

This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.

I Tu, Xinyi and Autiosalo, Juuso and Jadid, Adnane and Tammi, Kari and Klinker, Gudrun. A Mixed Reality Interface for a Digital Twin Based Crane. *Applied Sciences*, Vol. 11, no. 20, Special Issue "Smart Manufacturing Systems in Industry 4.0", pp. 9480, DOI: https://doi.org/10.3390/app11209480, October 2021.

II Tu, Xinyi and Autiosalo, Juuso and Ala-Laurinaho, Riku and Yang, Chao and Salminen, Pauli and Tammi, Kari. TwinXR: Method for using digital twin descriptions in industrial eXtended reality applications. *Frontiers in Virtual Reality*, Vol. 4, Research Topic "Exploring Synergies between the Digital Twin Paradigm and eXtended Reality", pp. 1019080, DOI: https://doi.org/10.3389/frvir.2023.1019080, January 2023.

III Tu, Xinyi and Ala-Laurinaho, Riku and Yang, Chao and Autiosalo, Juuso and Tammi, Kari. Architecture for data-centric and semantic-enhanced industrial metaverse: Bridging physical factories and virtual landscape. *Journal of Manufacturing Systems*, Vol. 74, pp. 965–979, DOI: https://doi.org/10.1016/j.jmsy.2024.05.016, June 2024.

Author’s Contribution

Publication I: “A Mixed Reality Interface for a Digital Twin Based Crane”

The author, with inputs from Juuso Autiosalo and Kari Tammi, conceptualized the study of an MR interface for a digital twin-based industrial crane. The author designed the architecture, the hardware and software setups, with help from Juuso Autiosalo and Adnane Jadid. The author developed the MR application software. The author designed and conducted evaluation of the control accuracy measurement, in consultation with Juuso Autiosalo and Adnane Jadid. The author wrote the original manuscript, which was reviewed by Juuso Autiosalo, Adnane Jadid, Kari Tammi, and Gudrun Klinker. The author developed the visualizations in the manuscript with support of Adnane Jadid. The overall study was supervised by Kari Tammi and Gudrun Klinker.

Publication II: “TwinXR: Method for using digital twin descriptions in industrial eXtended reality applications”

The author conceptualized the study on the TwinXR method, drawing on insights from Juuso Autiosalo, Riku Ala-Laurinaho, and Kari Tammi. The author, incorporating feedback from Juuso Autiosalo, designed the methodology including the TwinXR’s architecture, the material setups, and the workflows of development and utilization. The author, developed the proof-of-concept implementations of the TwinXR method with cranes and robot arms, of which Chao Yang helped the robot arm model conversion. The author wrote the original manuscript, which was reviewed by Juuso Autiosalo, Riku Ala-Laurinaho, Chao Yang, Pauli Salminen, and Kari Tammi. The author developed the visualizations in the manuscript with support of Juuso Autiosalo and Chao Yang. The overall study was supervised by Kari Tammi.

Publication III: "Architecture for data-centric and semantic-enhanced industrial metaverse: Bridging physical factories and virtual landscape"

The author conceptualized the study on the industrial metaverse architecture, leveraging the knowledge of Riku Ala-Laurinaho and Juuso Autiosalo. The author designed the architecture incorporating feedback from Riku Ala-Laurinaho. The author developed the case study of in-plant material flow tracking based on the proposed architecture. The author wrote the original draft, which was reviewed by Riku Ala-Laurinaho, Chao Yang, Juuso Autiosalo, and Kari Tammi. The author developed the visualization in the manuscript with support of Chao Yang. The overall study was supervised by Kari Tammi.

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Abbreviations

AAS Asset Administration Shell

A-box Assertion box

AI Artificial Intelligence

AIIC Aalto Industrial Internet Campus

API Application Programming Interface

AR Augmented Reality

DTDL Digital Twin Definition Language

DTW Digital Twin Web

FDTF Feature-based Digital Twin Framework

HMI Human-Machine Interface

HTTP Hypertext Transfer Protocol

IoT Internet of Things

MQTT Message Queuing Telemetry Transport

MRTK Microsoft Mixed Reality Toolkit

MR Mixed Reality

OPC UA Open Platform Communications Unified Architecture

PLM Product Lifecycle Management

ROS Robot Operating System

SAREF Smart Applications REFerence

T-box Terminology box

UI User Interface

URI Uniform Resource Identifier

VR Virtual Reality

WoT TD Web of Things Thing Description

WWW World Wide Web

XR Extended Reality

1. Introduction

The industrial landscape is undergoing a profound transformation towards Industry 5.0, which aims to reintegrate the human touch into the automated and data-driven framework of Industry 4.0 [161, 138]. Industry 5.0 emphasizes human-machine collaboration, sustainability, and personalized production, fostering a balance between smart technology and human ingenuity in industrial processes [75, 97]. Within this progressive context, the metaverse emerges as a significant concept, blending physical reality and digital virtuality [98]. This fusion is envisaged to redefine the traditional industrial frameworks, transcending the conventional boundaries to foster innovative manufacturing paradigms characterized by interactive, immersive, and tailored experiences [147, 63, 165]. This dissertation explores this transformation, focusing on the convergence of two core technologies: digital twins and extended reality (XR).

Digital twins are virtual representations of physical systems used for simulation, analysis, and control [146]. They enable the creation of digital replicas of physical assets, processes, or systems, enhancing optimization, predictive maintenance, and operational efficiency [124, 65, 78]. As integral components of the metaverse, they bridge the physical and digital spaces, enabling real-time data analysis and decision-making. Meanwhile, XR, encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), enhances human-machine interactions within the metaverse [25]. XR technologies facilitate immersive experiences, allowing users to intuitively interact with physical world and its digital twins, crucial for a range of applications from training and simulation to remote operations [32, 28, 145]. The industrial metaverse aims to unify a group of technologies including digital twins and XR into a cohesive framework that supports industrial activities. It seeks to transcend the capabilities of its constituent technologies by not only merging the physical and digital worlds but also enabling collaborative, interconnected industrial ecosystems. This ambitious integration demands a critical analysis of how digital twins and XR can be effectively synchronized to support real-time, scalable, and interactive industrial processes.

Despite the substantial strides in technical advancements, the integration of digital twins with XR technologies, and their incorporation into the broader framework of the industrial metaverse, is fraught with challenges. The thesis focuses on the three research gaps identified through: (1) Interactivity and evaluation of industrial XR systems with digital twins: The integration of XR and digital twins lacks dynamic interactivity and standardized evaluation methods, limiting effective control and measurement of XR applications in industrial settings. (2) Systematic integration of XR and digital twins: There is a lack of systematic methodologies for integrating XR with digital twins, resulting in non-scalable and bespoke solutions that fail to support diverse industrial applications efficiently. (3) Practical and comprehensive industrial metaverse architecture: Existing industrial metaverse architectures often focus narrowly on XR technologies without addressing the holistic needs for data integration and semantic enrichment, essential for operational effectiveness in industrial settings.

In response to these research gaps, this thesis first explores the development and application of XR interfaces for operating digital twin-based industrial systems, focusing on a MR interface for a digital twin-based overhead crane platform. This initial exploration into the industrial metaverse highlights the potential for improved human-machine interactions and operational efficiencies by enabling bi-directional data interactions and measuring control accuracy in integrating XR with digital twins at a specific application level.

The research then expands its scope to a more systematic approach, introducing the TwinXR method. This method underscores the robustness and scalability of integrating digital twin descriptions in industrial XR applications. Practical deployments, including overhead cranes and robot arms, demonstrate the potential of TwinXR in enhancing XR development and revealing the interoperability capabilities of digital twins across various industrial settings.

The culmination of this research is the proposition of a comprehensive architecture for the industrial metaverse. This architecture seamlessly integrates physical factory operations with the metaverse, illustrating a sophisticated amalgamation of digital twins and semantic models. A case study on in-plant material flow tracking underscores the practicality and scalability of this architecture, marking a significant step towards an interconnected and robust industrial metaverse.

In summary, this thesis charts the journey from Industry 4.0 to Industry 5.0 through the industrial metaverse, driven by the synergistic integration of digital twins and XR technologies. It represents a paradigm shift towards a more human-centric approach in industrial operations, underpinned by enhanced collaboration, innovation, and efficiency.

1.1 Research goal and questions

The impending convergence of digital twins and XR technologies within the industrial sector necessitates a thorough exploration to grasp their potential and challenges in shaping an integrated industrial metaverse. The overarching goal of this research is to advance the integration of digital twins and XR technologies in industrial settings, bridging identified gaps to enhance the development of an industrial metaverse, uncovering pathways that facilitate the evolution from Industry 4.0 to Industry 5.0 and beyond. The specific research questions below are tailored to address the three pressing research gaps identified through comprehensive literature review.

- *RQ1: How can XR interfaces be developed to operate digital twin-based industrial systems effectively?* (Publication I)
  RQ1 addresses the first research gap by exploring dynamic bi-directional interaction capabilities in XR solutions, aiming to enhance real-time data visualization and user control within industrial systems utilizing digital twins. The question investigates the technical development of an XR interface tailored for operating digital twin-based industrial systems. The aim is to understand how these interfaces can enhance human-machine interactions and operational efficiency in targeted industrial settings, marking an initial step towards realizing the industrial metaverse.

- *RQ2: How to integrate digital twins with XR across various industrial applications?* (Publication II)
  Directly responding to the second research gap, RQ2 explores the integration of digital twins with XR technologies in diverse industrial machinery and environmental settings with a systematic approach. The focus is on assessing the robustness and scalability of the approach in facilitating efficient and scalable XR development, and in revealing the data interchange and system interoperation capabilities of digital twins.

- *RQ3: How can a robust industrial metaverse architecture be designed to enhance smart factory operations?* (Publication III)
  Tackling the third gap, RQ3 explores the creation of a structured, practical industrial metaverse architecture that integrates digital and physical spaces more effectively, focusing on data integration and semantic enhancements to support complex industrial ecosystems. It involves identifying the key architectural components, technological underpinnings, and ensuring a seamless data flow and knowledge synchronization. The aim is to connect the physical factories with the metaverse.

Each research question is designed to develop actionable insights that address the specific limitations and gaps in the current landscape of industrial XR applications, digital twin integration, and metaverse architectures, ensuring that the proposed solutions contribute to an efficient, interconnected, and interoperable industrial metaverse.

1.2 Scientific contributions

The scientific contributions of this research are projected to be manifold, advancing the understanding and practical applications of XR, digital twins, and the industrial metaverse. Figure 1.1 depicts the overall relations among the three publications and their contributions, traversing from an focused MR application for operating a digital twin-based system in Publication I to a systematic TwinXR method across various industrial applications in Publication II, and culminating in an expansive metaverse architecture in Publication III. The key contributions per publication are detailed below.

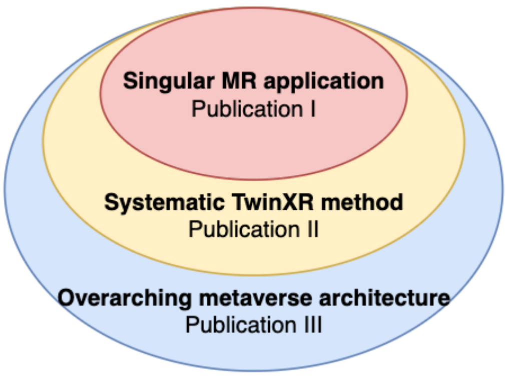


Figure 1.1. Relations among publications and their contributions.

1. **Novel MR interface for a digital twin-based system in industrial settings** (Publication I): Development and presentation of a novel MR application run on Microsoft HoloLens for operating a digital twin-based crane, defining a protocol for measuring the control accuracy of an MR application with holograms and an industrial crane, and implementing measurements to assess the control accuracy in crane operation.

2. **TwinXR method for enhanced synergies between digital twins and XR** (Publication II): Introduction of the TwinXR method which leverages digital twin descriptions of Smart Factory devices in creating and instantiating XR applications, development of an open-source Unity package [149] to facilitate TwinXR-compatible application development, and application of the TwinXR method in two industrial XR use cases

to validate the method, with the implementation source code publicly available [150, 148].

3. **Data-centric and semantic-enhanced industrial metaverse architecture bridging physical factories and virtual landscape** (Publication III): Introduction of a novel industrial metaverse architecture that links physical factories with their metaverse counterparts, emphasizing on data flow and knowledge synchronization through the integration of digital twins and semantic models, and affirmation of the efficacy and viability of the proposed architecture through a case study focused on in-plant material flow tracking.

These summarized contributions encapsulate the advancements in MR applications, the integration of digital twins and XR technologies, and the conceptualization of an industrial metaverse architecture, addressing the technical challenges and research gaps in human-machine interaction, industrial XR applications, and the industrial metaverse.

1.3 Thesis outline

This rest of thesis is organized into five main chapters, encompassing the literature review, methods and materials, results, discussion, and conclusion. Below is a brief outline of each chapter:

- **Chapter 2: Literature Review** covers existing literature and explores the concept of Industry 5.0, digital twins, XR, industrial metaverse, the synergies between digital twins and XR, outlines academic and industrial activities around the metaverse, and identifies the research gaps that this thesis aims to address.

- **Chapter 3: Methods and Materials** elucidates the research methods and materials employed, including the MR crane interface with its setups, architecture and development, and control accuracy measurement protocol, the TwinXR method with its architecture, setup, development, and utilization, as well as the industrial metaverse architecture consisting of the physical and metaverse spaces.

- **Chapter 4: Results** presents the core findings of the research, including the control accuracy measurement results for the MR crane interface, the proof-of-concept implementations of the TwinXR method with overhead cranes and robot arms, and a case study on in-plant material flow tracking employing the industrial metaverse architecture.

- **Chapter 5: Discussion** provides in-depth evaluation on the findings, highlights the merits and limitations of the work, envisions future research directions for the MR crane interface, the TwinXR method, and the industrial metaverse architecture, and finally presents the overall scientific and practical implications of the thesis.

- **Chapter 6: Conclusion** summarizes the key takeaways from the research, concluding the thesis, and reflecting on the contributions made towards advancing the understanding and application of the industrial metaverse, digital twins, and XR in modern industrial settings.

2. Literature review

This chapter examines the intertwined domains of Industry 5.0, digital twins, industrial XR, the synergistic integration of digital twins and XR, and the industrial metaverse, alongside outlining academic and industrial activities around the metaverse and identifying crucial research gaps. This exploration looks into the evolution, current trends, and potential industrial implications of these technologies. It elucidates how digital twins and XR are reshaping the industrial landscape, emphasizes the necessity of their effective combination, and explores the emerging concept of the industrial metaverse. The chapter culminates by pinpointing significant research gaps, setting the stage for the thesis to contribute towards resolving these challenges and propelling the industrial sector towards a more integrated and efficient future.

2.1 Industry 5.0

Industry 5.0 marks a significant evolution in the industrial paradigm, building upon the digital foundation laid by Industry 4.0 while reintroducing the human element into manufacturing and production processes [161, 138]. This new phase emphasizes the collaboration between humans and smart systems, aiming to create more sustainable, resilient, and personalized production environments [75, 97].

Human-centric approach [99]: At the heart of Industry 5.0 lies a human-centric approach, where the value of human creativity, ethics, and capabilities are paramount. This approach seeks to harness the strengths of both humans and machines, leveraging advanced technologies to augment human skills rather than replace them. The focus is on enhancing human well-being, job satisfaction, and creativity within the industrial setting.

Technological synergy [83]: Industry 5.0 is characterized by the synergistic integration of cutting-edge technologies such as artificial intelligence (AI), robotics, the Internet of Things (IoT), and advanced materials. These technologies are not just tools but partners in the production process, designed to work alongside humans to optimize efficiency, flexibility, and customization.

Sustainability and resilience [44]: Sustainability is a cornerstone of Industry 5.0, driving the transition towards more eco-friendly and resilient industrial practices. This involves not only reducing waste and energy consumption but also designing systems that can adapt and recover from disruptions. Industry 5.0 envisions a circular economy where resources are reused and recycled, aligning industrial practices with environmental stewardship.

Personalization and customization [108]: The shift towards personalized production is another defining feature of Industry 5.0. Leveraging the capabilities of digital twins and advanced manufacturing techniques, industries can now offer products tailored to individual preferences without sacrificing efficiency or increasing costs. This level of customization is transforming consumer expectations and the manufacturing landscape.

Collaborative ecosystems [8]: Industry 5.0 promotes the creation of collaborative ecosystems, where businesses, governments, and educational institutions work together to foster innovation and growth. These ecosystems are powered by data sharing and collaborative platforms, enabling a more integrated approach to solving complex industrial challenges.

In summary, Industry 5.0 represents a transformative movement towards more human-centric, sustainable, and resilient industrial systems. By blending the strengths of human intuition and creativity with the capabilities of advanced technologies, Industry 5.0 is setting the stage for a new era of industrial innovation and efficiency.

2.2 Digital twins

The origin of the digital twin concept traces back to the visionary work of Michael Grieves in the early 2000s, initially proposed within the context of Product Lifecycle Management (PLM) [50]. Grieves' foundational model introduced digital twins as a paradigm encompassing the physical and virtual spaces, bridged by a dynamic flow of data facilitating real-time communication. This framework was instrumental in mirroring the life cycle of physical products, from inception through obsolescence, enabling unprecedented levels of monitoring, analysis, and optimization. The term "digital twin" gained prominence in 2010 when NASA envisioned its application in space vehicles as part of simulation-based system engineering [92]. In this context, digital twins were utilized for the probabilistic simulation of aerospace vehicles and integrating real-time data from various sensors, primarily for condition monitoring and predictive maintenance purposes. This adoption by NASA marked a significant milestone in the evolution of digital twins, expanding their usage across diverse domains and applications [101]. Since then, the scope of digital twins has undergone significant expansion and diversification. Initially confined to mirroring individual physical assets, the concept has evolved to encompass complex systems and processes, broadening its applicability across industries such as manufacturing [69], healthcare [123], urban planning [133], and beyond. This evolution reflects in the plethora of definitions that have emerged, each tailored to the specific nuances and demands of different domains. While these definitions universally recognize digital twins as dynamic, digital replicas of physical entities, continuously updated with real-time data for simulation, analysis, and optimization, it is crucial to differentiate them from the concept of "digital shadow" [132]. Unlike digital twins, digital shadows are passive data constructs that reflect changes in their physical counterparts [1] without the capability for autonomous decision-making or real-time interaction. The distinction is critical as contemporary digital twin applications underscore their transformative potential, extending beyond traditional simulation and modeling. Today's digital twins offer sophisticated capabilities for predictive maintenance, operational optimization, predictive insights, and autonomous decision-making [119, 14, 146, 130]. In the context of smart manufacturing, [78] highlighted the pervasive role of digital twins across various dimensions, including manufacturing assets, people, factories, and production networks.

The Feature-based Digital Twin Framework (FDTF), proposed by [7], delineated ten technical features of digital twin system, namely, data link, computation, coupling, identifiers, security, data storage, user interfaces, simulation models, analysis, and Artificial Intelligence (AI). This framework marked the functional requirements necessary for implementing digital twins and emphasized the importance of user interfaces as a critical component for operator interaction with digital twin systems. These guiding principles were later expanded in [2] and demonstrated with an industrial crane, where digital twins provided data interfaces leveraging digital twin description documents, which this thesis refers to as a "DT document". Furthering this exploration, [6] proposed the Digital Twin Web (DTW), resembling the structure of the World Wide Web (WWW), focusing on the significance of connectivity, scalability, and interoperability within the digital twin network. DTW facilitates the management and distribution of DT documents, effectively organizing the metadata of digital twins. [6] also introduced the "Twinbase", the first implementation of DTW server, of which the utility was demonstrated in controlling a Smart Factory [86] and in combining digital twins and XR application in Publication II of the thesis. Building upon these foundational frameworks, the broader implications of the FDTF have profoundly influenced the design of the industrial metaverse architecture proposed in this thesis. The current work not only adapts but also expands upon the essential elements from the FDTF to meet the specialized needs of the industrial metaverse. It does so by elaborating, extending, and reinterpreting each component's functionality within the architecture. By organizing these components into distinct functional blocks, the architecture is finely tuned for complex industrial applications. Moreover, it distinctly sets itself apart from traditional digital twin systems by redefining them within the context of the industrial metaverse as human-in-the-loop digital twin systems.

Despite the significant advancements and broadening scope of digital twins, current implementations face challenges in data visualization and interaction. The complexity and volume of data generated by digital twins can be daunting, making it difficult to present this information in an accessible and user-friendly manner. This issue is compounded by a notable shortage of intuitive XR interfaces that could enable more immersive and interactive exploration of digital twin data. Addressing these limitations is crucial for unlocking the full potential of digital twins, especially as we move towards more integrated and interactive systems in the context of Industry 5.0. Enhancing XR support for digital twins will not only improve data usability and comprehension but also facilitate a deeper human-machine synergy, crucial for the next generation of industrial applications.

In summary, the journey of digital twins from a nascent PLM tool to a cornerstone of modern digital strategies underscores their transformative potential. As digital twins continue to evolve, their integration into diverse industrial and societal contexts promises to usher in a new era of efficiency, customization, and innovation, aligning with the overarching goals of Industry 5.0. Yet, the journey faces hurdles particularly in data presentation and the lack of XR interfaces, which must be addressed to enhance user interaction and unlock the full potential of digital twins, paving the way for more immersive and interactive industrial ecosystems.

2.3 Industrial extended reality

XR is revolutionizing the industrial sector, encompassing a spectrum of technologies blending the virtual and real worlds. This spectrum includes VR, AR and MR, each bringing unique capabilities to the industrial landscape as detailed below.

- VR immerses users completely in a fully digital environment [19]. In manufacturing, VR is utilized for training, simulating complex processes, and designing products in a fully controlled virtual space [24].

- AR overlays digital information onto the physical world [22]. In industrial contexts, AR can be used for maintenance, training, and enhancing operational efficiency by providing real-time data and graphical overlays

[100].

- MR combines elements of both AR and VR, anchoring virtual objects to the real world and allowing for interaction with these objects [140]. MR is particularly transformative in industrial applications, enabling workers to interact with digital twins of machinery or processes in real-time [67].

In the evolving landscape of Industry 5.0, XR applications are playing a critical role in making manufacturing systems more agile and adaptable, especially for small-scale, economically sustainable production [33]. The integration of human operators into these advanced production processes, facilitated by human-machine interfaces (HMIs), is becoming increasingly important to manage the growing complexity in manufacturing [72, 47]. The adoption of mobile devices with multi-modal interaction capabilities, such as overhead displays, tablets, and smartphones, in manufacturing and production processes has catalyzed the integration of XR [82].

In the domain of crane operation, research has been extensively conducted in VR crane training [85, 126, 30, 139, 112]. Several studies also integrated AR/MR in crane operation: [84] proposed conceptual speech-based HMIs equipped with AR for mobile crane control; [5] explored the use of wearable AR for facilitating knowledge sharing among crane maintenance technicians; [76, 23, 116] integrated building information modeling, videos, or safety information with AR for crane operators to enhance safety and efficiency. However, these solutions were limited to one-directional data flow between the crane and the XR interface. In other words, these XR systems were only used to improve data visualization via either fully simulated immersive environment or superimposing digital content, without involving any interactive component through which users could directly control the crane through its digital twin.

This limitation in the crane operation domain exemplifies a broader research gap within industrial XR applications, as identified by [70] in their review of existing literature. XR applications commonly depend on static displays and unidirectional data streams from machines to interfaces. This limitation hampers the ability of users to interact with and control physical processes effectively, highlighting the necessity for systems that facilitate more dynamic and interactive engagements. The integration of digital twins as data sources becomes crucial in this context, offering a solution for seamless data integration that can significantly enhance the interactivity and responsiveness of XR environments.

Transitioning to evaluation, common methods for assessing industrial XR applications included user studies, design studies, case studies, implementation validation, system performance tests [70, 35, 36, 52, 88]. However, despite these diverse approaches, the literature reveals a notable absence of standardized methods specifically tailored for quantitatively measuring the control accuracy in XR control applications. This gap highlights the need for developing reliable measures to assess XR systems' precision and effectiveness in industrial environments.

In summary, XR technologies are propelling substantial progress in the industrial arena with various applications, yet their true capacity remains untapped due to challenges such as the need for dynamic data integration with digital twins and the absence of standardized methods to evaluate XR control systems' effectiveness. By addressing these issues, XR can enhance its capabilities, leading to more interactive and efficient industrial applications.

2.4 Synergizing digital twins and extended reality

The integration of digital twins and XR technologies is significant in Industry 5.0 contexts. While digital twins provide a detailed data backbone, XR interfaces enrich this data with immersive and interactive user experiences, as highlighted in studies by [169, 81]. The utility of this integration is evident in diverse industrial applications, including AR in reconfigurable factories [9], leveraging digital twins in VR for training purposes [110], simulating digital twins in XR for cobotic workstation evaluation [159], and XR interfaces for crane virtual training and remote monitoring [163]. [29] conducted a thorough systematic literature review and bibliometric analysis on the intersection of digital twins and XR in industrial contexts, demonstrating the practical benefits of this integration.

However, the literature reveals a pervasive gap in developing systematic methodologies for integrating these technologies. The aforementioned studies primarily concentrated on developing and demonstrating technical designs and implementations of XR applications for digital twin systems in individual use cases or domain-specific implementations, rather than establishing a scalable and replicable framework. This is underscored by a reliance on bespoke XR development, as addressed in [46, 57, 21], which is often cumbersome and not suited for dynamic or scalable application. The process of adapting and customizing these XR applications on the fly necessitates specialized XR development tools, tasks that domain experts, despite their deep understanding of specific machine requirements and operational contexts, seldom achieve alone. Moreover, establishing connections between the machinery's physical aspects and the XR application's digital interface often involves a repetitive and meticulous process, unique to each application instance. The fundamental challenge here is the non-standardized nature of current XR development processes, which limit the ability to leverage digital twins across varied industrial contexts effectively. The industry currently lacks a unified approach to embedding interoperability and real-time data integration within XR platforms, which is essential for achieving the full potential of digital twins in operational settings.

Moreover, while the use of shared ontologies has been suggested as a key enabler for integrating shared knowledge representation with XR to enable adaptive interface [15], practical implementations of such frameworks remain scarce. Existing initiatives have made strides in knowledge-based XR environments: [48] introduced a method for knowledge formalization and management in industrial VR applications by enabling the formal recording and external storage of product/process knowledge for later access; [40, 41] proposed the idea of knowledge-based, explorable XR environments that offered enhanced capabilities for monitoring, analyzing, and controlling XR environments, including user and asset behaviors. However, these solutions often do not integrate the systems deeply with digital twins, missing opportunities for enhanced data manipulation and interaction.

On the other hand, despite the critical role of information management-oriented digital twins in bridging data silos through semantic links and information flow among different assets and applications [77], many implementations still fall short in establishing robust mechanisms for semantic data integration. This integration is essential for managing the complex data ecosystems prevalent in modern industrial environments. Established standards such as Schema.org [128], GS1 Web Vocabulary [51], and Smart Applications REFerence (SAREF) [127] employ machine-readable ontologies to facilitate communication and standardize data descriptions. A critical element in this structure is the DT document, which embodies common data ontologies to describe digital twins, with specifications that include the Digital Twin Definition Language (DTDL) [90], the Web of Things Thing Description (WoT TD) [68], and the Asset Administration Shell (AAS) [109]. The thesis leverages the framework proposed in [2]. However, the integration of these standards and specifications into industrial XR applications remains sparse and underdeveloped.

Recent systematic literature review by [27] pinpointed the immaturity of data management practices in digital twin deployments, emphasizing the necessity for standardized approaches and better integration practices. These studies call for enhanced research efforts towards adopting industry standards and fostering interoperability among digital twins, which could significantly bolster the effectiveness of XR applications in industrial settings.

In summary, while the integration of digital twins and XR stands at the forefront of the Industry 5.0 evolution by enhancing interactive capabilities and operational efficiency, challenges persist in the bespoke nature of XR development and the intricacies of data integration. Embracing shared knowledge frameworks like ontologies could streamline this synergy, promising more adaptable and intuitive XR environments that fully leverage the rich data landscapes of digital twins, thereby driving forward the industrial metaverse and Industry 5.0.

2.5 Industrial metaverse

The metaverse, a prominent concept in technology and culture, brings varied interpretations and is subject to robust discussions on its scope and implementation. [98, 96] envisioned the metaverse as a connected web of continuous, immersive, and persistent multi-user environments that integrate physical reality with digital virtuality. While the EU prefers the term "virtual world" to emphasize visions aligned with European values of digital sovereignty and inclusivity [61], this thesis adopts the term "metaverse" due to its widespread recognition and particular relevance to the specialized focus, the "industrial metaverse". For the purposes of clarity, we define the metaverse as "a continuum of physical and virtual systems, interconnected and intertwined in ways that allow for seamless transitions and interactions, which stands distinct from merely virtual environments and virtual reality in its depth of connection to the physical world, and its constant synchronization and reflection of real-world dynamics".

This foundation leads to the "industrial metaverse", specially designed for industrial use. According to [168], it shares core aspects of the general metaverse, like digital assets, man-in-the-loop, and social networks, but stands out for its focus on industrial process value and ability to simulate various industrial components such as machinery, personnel, materials, activities, and processes. This concept of the industrial metaverse, as envisioned by [168], is akin to a novel digital twin system, focused on human-in-the-loop dynamics, simulating industrial activities, enabling transactions of industrial value, and fostering collaborations between humans and machines. This notion aligns with [73], who view the industrial metaverse as an extension of a workspace's digital twin, playing a key role in enhancing interactions with physical entities and visualizing cyber-physical systems.

The industrial metaverse provides an interactive platform where diverse teams and clients can engage and collaborate effectively, offering customized experiences [20]. This shift is critical in revolutionizing how factory staff engage with technology, introducing collaborative and customizable interfaces that are essential for effective control, monitoring, and maintenance of industrial processes. Industrial metaverse applications have been explored through various case studies: [162] focused on metaverse applications in fluid machinery, particularly pumps and fans, highlighting remote operation and monitoring capabilities; [73] examined metaverse applications in remote manufacturing, specifically in machine health, process monitoring, control, and maintenance of ball screws, showcasing real-time data connectivity and expert engagement for maintenance guidance; [102] explored data-driven intelligent transportation systems within the metaverse, utilizing AR and VR for data visualization and remote vehicle operation; [3] investigated the digital factory metaverse concept, focusing on VR-based multi-user experiences to enhance factory operations.

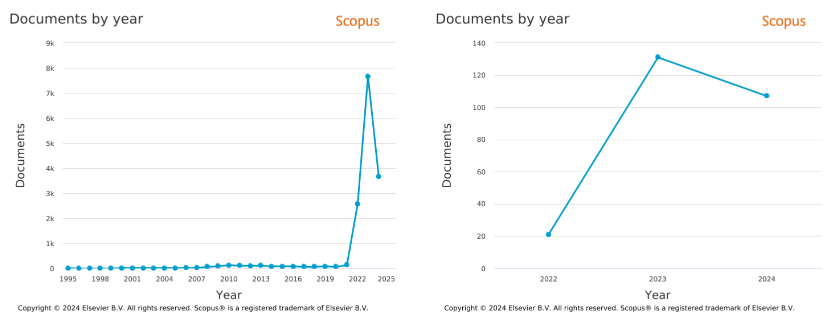
Metaverse development, still in its nascent stages, lacks a universally accepted architecture. [79] proposed a seven-layer framework detailing the developmental stages of the metaverse, starting from infrastructure and progressing through human interface, decentralization, spatial computing, creator economy, discovery, and experience. This structure implies a developmental progression from foundational infrastructure to operational ecosystems. In contrast, [34] streamlined this concept into a three-layered architecture, encompassing the physical world (infrastructure layer), the virtual world (ecosystem layer), and an intermediate interaction layer. [74] outlined a three-stage metaverse evolution as a "digital twins-native continuum": initially digitizing the real world, followed by a phase where digital creators shape various virtual worlds, culminating in a self-sustained metaverse that balances physical and virtual realities in a coexistent, yet independent manner.

While these metaverse architectures mainly cater to consumer applications, industrial metaverses require enhanced reliability, stringent security, and comprehensive interoperability, especially for integration with existing systems. Addressing these needs, [168] devised an industrial metaverse architecture composed of four layers, encompassing basic elements like personnel and equipment, a perception layer for real-time data processing, a service layer divided into foundational, engine, and analytical platforms, and an application layer offering diverse functionalities across the industrial system. [73] introduced a "5C" framework for cyber-physical industrial metaverse systems, focusing on data acquisition, conversion, time-machine data management, information visualization for human-machine interaction, and a configuration layer for multi-sourced data integration. However, these architectures frequently fall short in offering detailed, actionable plans for implementation. Moreover, there's a tendency in existing research to disproportionately highlight the role of XR technologies, overlooking the need for a comprehensive, platform-based strategy that's crucial for seamlessly integrating digital and physical worlds.

In summary, the concept of the industrial metaverse stands as a transformative force for industry, promising to revolutionize interactions, simulations, and operations through its immersive, unified environments. However, to fully harness its potential, the challenges of developing robust, practical architectures and ensuring a balanced, all-encompassing approach that goes beyond XR must be addressed. This will pave the way for a truly integrated and efficient industrial metaverse.

2.6 Academic and industrial activities related to the metaverse

Research related to the metaverse has shown a dramatic increase in recent years, as depicted in Figure 2.1. From nearly negligible numbers prior to 2020, document publication has surged to over 7500 by 2023, highlighting a burgeoning interest in metaverse technologies. Conversely, the industrial metaverse, while sharing a similar trend of gaining attention since 2022, has seen significantly fewer publications, peaking at around 130 documents in 2023. This disparity underscores the emerging nature of the industrial metaverse within the broader metaverse discourse and highlights substantial opportunities for research and development. The trend reflects the potential of metaverse solutions to revolutionize traditional industrial operations, suggesting a critical and growing focus on integrating these technologies within various industrial applications. This emerging gap emphasizes the need for targeted research efforts to understand and exploit the unique aspects of the industrial metaverse, where significant advancements can still be made to harness its full potential for transforming industrial ecosystems.



(a) **(b)**

Figure 2.1. Document by year statistics from Scopus database (date: 12 May 2024) (**a**) TITLE-ABS-KEY ("metaverse") ; (**b**) TITLE-ABS-KEY ("industrial metaverse").

From an industrial perspective, the metaverse is witnessing significant growth. The global metaverse market is projected to expand from USD 116.74 billion in 2024 to USD 669.96 billion by 2029, showcasing a compound annual growth rate of 41.83 % [94]. This growth is attributed to the rising demand in media, entertainment, and gaming sectors, alongside substantial investments by key market players [42]. Conversely, the industrial metaverse is rapidly emerging as an arena of enormous potential, with projections suggesting it may soon overshadow consumer and enterprise applications [103].

Prominent corporations such as Meta, Microsoft, NVIDIA, and now Apple are heavily investing in metaverse technologies. Meta has committed nearly USD 50 million to global metaverse research and development, focusing on XR technologies to pioneer the next evolution in social connectivity [89]. Microsoft is enhancing collaborative virtual environments, enterprise, and industrial solutions within the metaverse, integrating their comprehensive hardware and software capabilities [91]. Meanwhile, NVIDIA is fortifying the foundational technologies that empower the metaverse through their Omniverse platform [105], forging strategic partnerships with Siemens [135] and Microsoft [104] to advance industrial metaverse applications. Apple has entered the metaverse with its Vision Pro headset, focusing on spatial computing to merge digital content seamlessly with the physical world, enhancing user interaction and presence [4]. These initiatives underscore a strategic commitment to developing metaverse technologies that cater to both general consumer and specialized industrial uses.

2.7 Research gaps

This thesis identifies specific research gaps stemming from a comprehensive review of existing literature. These gaps are methodically linked to the research questions defined at the onset of this study, which address the previously documented shortcomings and aim to contribute to the targeted solutions within the scope of the interplay among digital twins, XR, and industrial metaverse.

1. **Interactivity and evaluation of industrial XR systems with digital twins**: The industrial application of XR technologies including VR, AR, and MR, has revealed substantial gaps in the dynamic integration and functionality within industrial settings. Existing XR solutions often rely on unidirectional data flows that restrict meaningful interaction and control over physical systems, particularly in domains such as crane operations [85, 126, 30, 139, 84, 5, 76, 23, 116]. A significant gap is the lack of actual integration of digital twins with XR systems, which would enable bi-directional data exchanges and enhance system interactivity. Additionally, the absence of standardized methods for assessing XR application accuracy highlights the need for developing robust evaluation methodologies to accurately measure the effectiveness and precision of XR technologies in industrial applications [70, 35, 36, 52, 88]. These gaps underline the essential need for improved interactivity and robust evaluation standards to fully utilize the capabilities of XR technologies in conjunction with digital twins in industrial settings.

2. **Systematic integration of XR and digital twins**: The integration of XR technologies with digital twins in the industrial sector faces significant hurdles due to the lack of systematic exploration and standardized methodologies for scalable development. Currently, the creation of XR applications often remains a bespoke process, specifically tailored to individual use cases and environments, making it cumbersome and non-scalable [46, 57, 21]. Furthermore, the industry lacks a unified framework to efficiently link information-management digital twins with knowledge-based XR, which is crucial for supporting diverse operational contexts and ensuring operational flexibility and robustness in XR implementations [70]. These challenges are compounded by standardization issues, where existing integration processes frequently require manual interventions, which are resource-intensive and prone to errors, impeding the scalability and adaptability of XR and digital twin technologies [77]. Additionally, there is a significant deficiency in standardized procedures to ensure consistent and effective communication between physical machinery and their digital counterparts, vital for promoting interoperability and real-time data interaction within industrial systems. The need for an integrated framework is evident, one that not only supports the diverse requirements of industrial environments but also facilitates the development of more adaptable and intuitive XR environments, leveraging the rich data landscapes of digital twins to advance industrial capabilities effectively.

3. **Practical and comprehensive industrial metaverse architecture**: Current metaverse frameworks primarily focus on consumer applications [79, 96, 34, 74], often neglecting the unique challenges and complexities of industrial settings. Additionally, while existing literature on the industrial metaverse, such as the works of [168, 73], provides valuable insights, they largely present conceptual models without detailed practical guidelines for real-world implementation. Moreover, existing case studies, including [162, 73, 102, 3], while insightful, often disproportionately focus on XR technologies. This emphasis, though crucial, frequently overlooks the need for a holistic, platform-oriented approach that is essential to the metaverse's nature, an integrative digital-physical continuum. These studies frequently downplay essential aspects such as data integration and semantic enrichment, critical for a fully functional industrial metaverse.

In summary, these gaps highlight the need for more robust, scalable, and practical solutions in the XR and digital twins' integration, and the development of a comprehensive industrial metaverse architecture. Addressing these gaps is essential to advance the field towards more efficient, interconnected, and interoperable Industry 5.0.

3. Methods and materials

This chapter elucidates the methods and materials utilized in this research, encompassing the development and the measurement protocol of an MR application operating a digital twin-based crane with its hardware and software setups, the TwinXR method's architecture, material setup, development, and utilization, as well as the industrial metaverse architecture consisting of the physical and metaverse spaces.

3.1 Mixed reality application operating a digital twin-based crane

This section presents the hardware and software setups as well as the development of an MR application for operating a digital-twin based overhead crane. As depicted in Figure 3.1, users equipped with the Microsoft HoloLens 1 device can engage with the crane through the MR application in two ways with both control and monitoring capabilities. Additionally, this section introduces a systematic measurement protocol to evaluate the application's control accuracy.

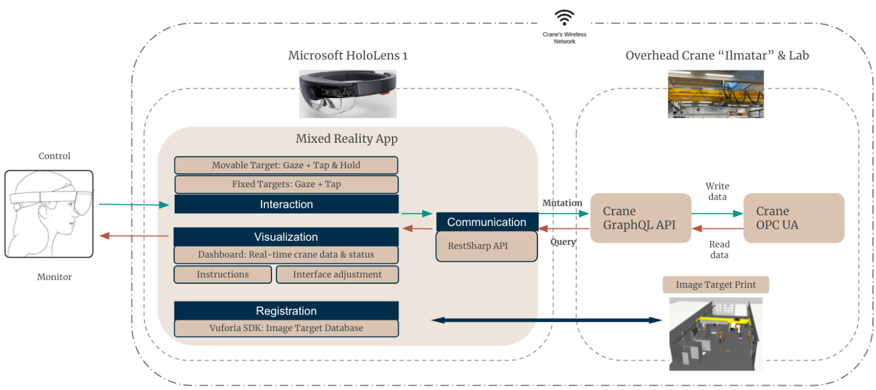


Figure 3.1. Overview of the MR application on the Microsoft HoloLens 1 device, through which users can operate an overhead crane equipped with its software system (Publication I).

3.1.1 Hardware and software setups for the mixed reality application

The MR application runs on the Microsoft HoloLens (1st Generation), a pioneering head-mounted device operating on the Windows Mixed Reality platform. Its see-through display overlays digital content onto real-world environments, enhanced by various sensors for spatial understanding and user input interpretation. HoloLens 1 features multiple networking capabilities, including Wi-Fi 802.11ac. For software development, key tools include Unity game engine for 3D application creation, Microsoft Mixed Reality Toolkit (MRTK) for HoloLens capabilities, PTC Vuforia SDK for image registration and tracking, and RestSharp Application Programming Interface (API) for Hypertext Transfer Protocol (HTTP) communication with the GraphQL wrapper.

This work employs the industrial overhead crane named "Ilmatar" at the Aalto Industrial Internet Campus (AIIC), which serves as a digital twin-based platform, providing an experimental environment for students and researchers to explore and conduct studies related to smart factory applications. The Konecranes CXT family crane features three physical components: a hoist, trolley, and bridge, offering movement capabilities across three dimensions, as illustrated in Figure 3.2, and can lift loads up to 3.2 tons. It is operated manually and equipped with an external control feature for communication via an Open Platform Communications Unified Architecture (OPC UA) server, offering extensive control and status variables. A GraphQL wrapper acts as an intermediary, translating client queries into OPC UA service requests and vice versa. The crane's network connectivity allows external devices to interact with both the GraphQL API and OPC UA server, facilitating remote control and monitoring through a Wi-Fi connection.

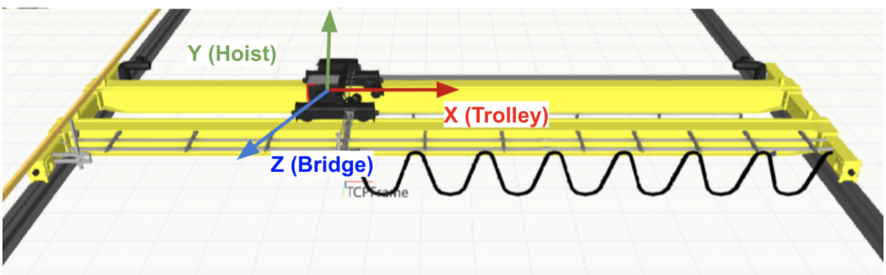


Figure 3.2. Overview of Crane "Ilmatar" components (Publication I).

3.1.2 Mixed reality application development

Within the MR application, functionalities are organized into four distinct modules: interaction, visualization, registration, and communication. This section covers the functionality and development of each module.

Interaction module facilitates crane control through 3D sphere-shaped holograms, offering both movable and fixed target control of the crane's hook position, as illustrated as part of Figure 3.3. This module is developed using the MRTK and Unity's input system, supporting gaze and "tap and hold" gestures. It features a script that continuously calculates the difference between the crane's current position and the selected target across its subsystems, guiding its movement. The process necessitates pre-calibrating the crane's position in physical space with its representation in the Unity scene. This calibration involves aligning the crane with fixed targets, reading its positions, and establishing a linear relationship between the physical and virtual coordinates, thus ensuring accurate target positioning within the system.

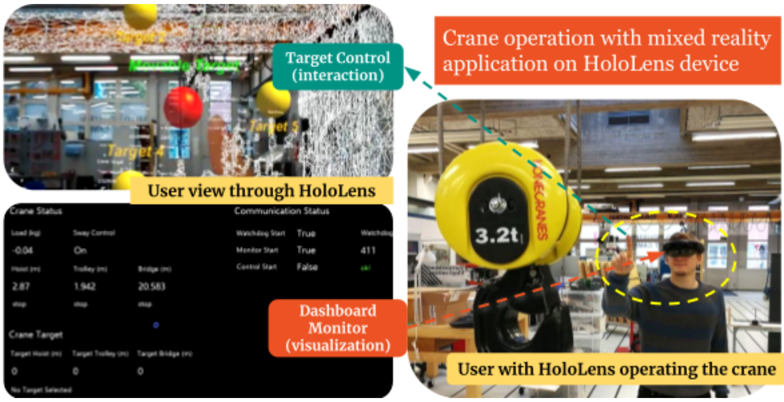


Figure 3.3. User view through HoloLens device while operating the crane, including target control holograms, and a dashboard with real-time crane status (Publication I).

Visualization module provides a dashboard for real-time crane status (as illustrated as part of Figure 3.3), interactive instructions for ease of use, and interface adjustments for user preference. This module is constructed using prefabricated User Interface (UI) components from the MRTK, ensuring both aesthetic appeal and functional interactivity. These elements, like collision-based buttons and toggles, are designed to provide audio-visual feedback to accommodate various input types. This setup utilizes "Interactable" events within the prefab components to facilitate user interactions, such as navigating through instructional pages and adjusting the MR interface by toggling the visibility of certain holographic elements.

Registration module ensures the accurate placement of virtual content in the physical environment. This module is developed using the Vuforia AR SDK within Unity, utilizing its image target, device tracking, and extended tracking capabilities. Figure 3.4 demonstrates the registration module development in Unity scene. The process involves importing an image target database and a spatial mapping mesh of the lab into Unity. A bounding box hologram is placed around the image target to aid in user orientation during registration. The alignment of the holograms with the physical environment is achieved by matching the image target's pose in Unity with its physical counterpart in the lab. This setup allows for accurate positioning of holograms relative to the user's view through the HoloLens, enhancing the application's immersive experience.

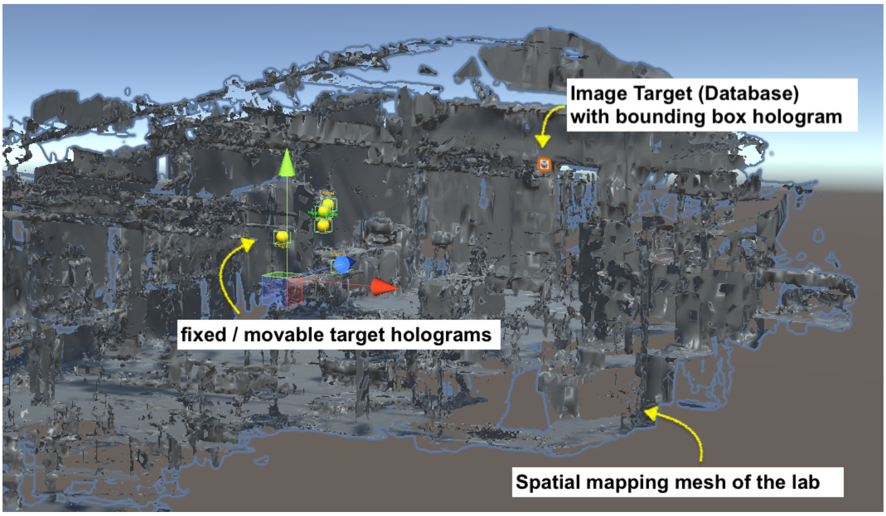


Figure 3.4. Registration development in Unity scene with the spatial mapping mesh, target holograms, image target, and its bounding box (Publication I).

Communication module acts as a gateway between the crane and the application, enabling data exchange for control and monitoring purposes. The RestSharp API is utilized to issue HTTP requests to the crane's GraphQL wrapper. These requests are of two types: query requests for reading data and mutation requests for writing data. As illustrated in Figure 3.5, this module comprises three crucial components: the Watchdog function, Monitor function, and Control function. The Watchdog function manages the interaction module's access by regularly updating the access code and watchdog value through mutation requests. The Monitor function maintains real-time access to crane data, displaying status updates on the dashboard via query requests. Lastly, the Control function dynamically alters the crane's movement speed and direction, adjusting according to the difference between the crane's current position and the selected target, communicated through mutation requests. This structure facilitates a bidirectional data flow, ensuring seamless interaction between the MR application, the crane system, and the GraphQL server.

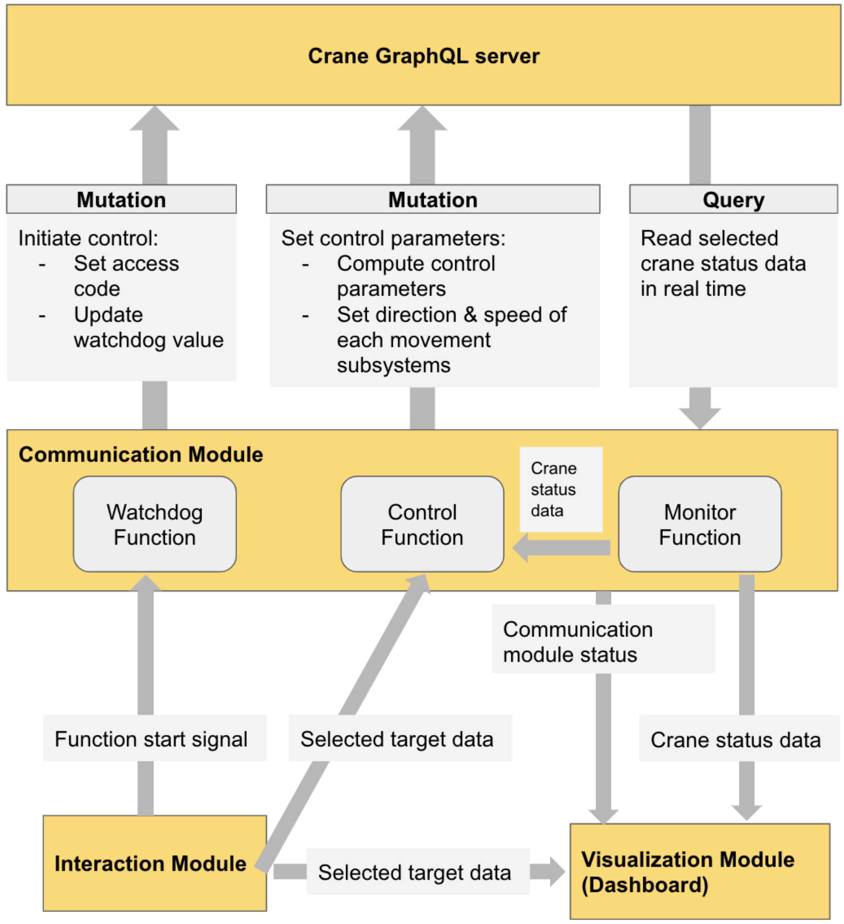


Figure 3.5. Communication module with the watchdog, control, and monitor functions, facilitating the bi-directional data flow among the visualization module, interaction modules, and the crane GraphQL server (Publication I).

3.1.3 Control accuracy measurement protocol

To evaluate the performance of the MR application quantitatively, the work develops a measurement protocol on the accuracy of the crane target control using the MR application. The protocol organizes the process into distinct steps, each with specified time frames and actions. The overall protocol, shown in Table 3.1, involves 20 repeat tests, beginning with an initial registration phase, followed by measurements with two specific control targets. Table 3.2 further details these measurements, outlining a series of view and movement changes within allotted times. In these tables, the notations X, Y, and Z correspond to the crane's trolley, hoist, and bridge components, as depicted previously in Figure 3.2. The procedure is detailed as follows:

Table 3.1. Overall measurement protocol for control accuracy (Publication I).

Test	Procedure	Time Allocation
Test 1	Registration	20 s
	Target 1 measurement	80 s
	Target 2 measurement	80 s
Test 2	Registration	20 s
	Target 1 measurement	80 s
	Target 2 measurement	80 s
...	repeat the unit test 20 times	...
Test 20	Registration	20 s
	Target 1 measurement	80 s
	Target 2 measurement	80 s
	Time sum	**60 min**

1. **HoloLens and crane setup**: Begin by powering up the HoloLens and launching the crane's MR application. Then, turn on the crane and enable its manual operation.

2. **Hologram registration**: Approach the image target until a green outline appears and aligns with the target, signaling successful registration. This step should be conducted within 20 seconds.

3. **Target selection and position recording**: Select the first target via an air-tap on its hologram and log the positions of the crane's components as displayed on the dashboard. Repeat for the second target. This step is a one-time requirement per target due to consistent target positions across different setups.

4. **Manual crane movement**: Manually maneuver the crane to align with the selected target, adjusting the position as needed from various angles and directions based on a predefined sequence and time allocation. Record the crane's actual position after alignment. This step is iterated for each target, with each unit measurement lasting 80 seconds, involving adjustments from different perspectives and directional fine-tuning as per the protocol.

5. **Test repetition**:Redo the registration and manual alignment steps for both targets, completing one unit test. This process is repeated 20 times to ensure thorough testing.

Table 3.2. Unit measurement protocol for control accuracy (Publication I).

View	Moving Direction	Time Allocation
XY	X	10 s
ZY	Z	10 s
XY	X	5 s
ZY	Z	5 s
XY	Y	10 s
	X	5 s
	Y	5 s
	X	5 s
ZY	Z	10 s
	Y	5 s
	Z	5 s
	Y	5 s
	Time sum	**80 s**

This structured approach ensures a systematic assessment of the MR application's control accuracy by meticulously documenting the crane's position in relation to selected holographic targets, providing a comprehensive evaluation of the system's performance.

3.2 TwinXR method for using digital twin description in industrial extended reality applications

This section explores the foundational structure and components of the TwinXR method, highlighting its architectural design, material setup, and the functional workflows for development and application in industrial settings. The TwinXR method is structured around a three-layered architecture, as illustrated in Figure 3.6, which facilitates seamless data flow and interaction across the Smart Factory, DT document, and XR application layers.

3.2.1 Architecture and material setup of the TwinXR method

The TwinXR method's architecture is designed to support a robust and efficient integration of digital twins with XR technologies. At the core of this architecture are three interconnected layers:

The **Smart Factory layer** incorporates physical machines, such as cranes and robot arms, each linked to a digital twin and equipped with XR interfaces. These machines, despite their variety, share common XR

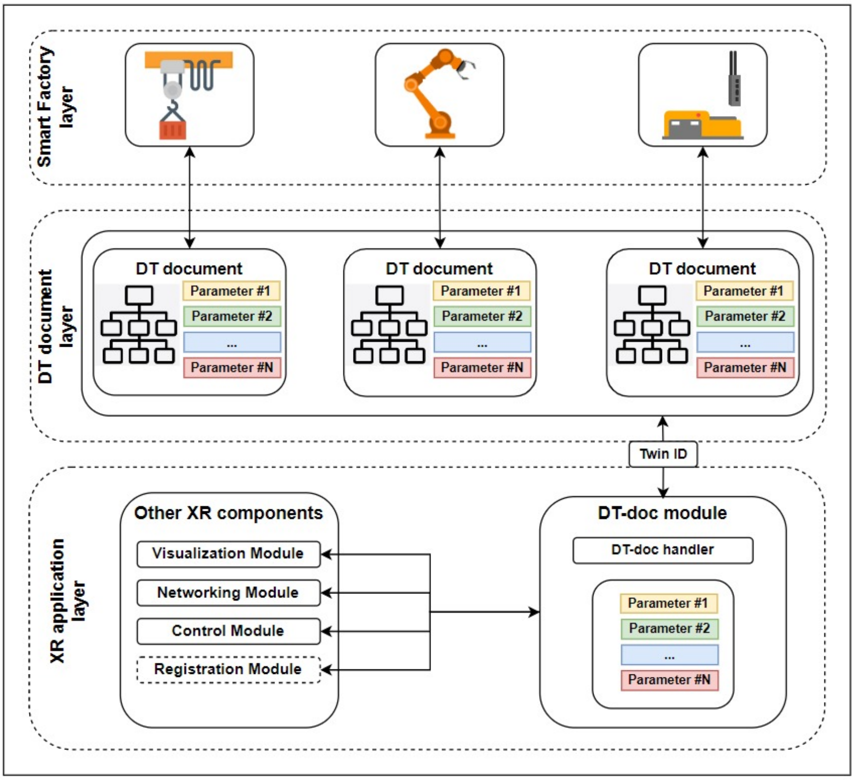


Figure 3.6. Overall design of the TwinXR method, featuring a three-layered architecture encompassing Smart Factory, DT document, and XR application layers (Publication II).

parameters like device name, load weight, and factory location coordinates. The TwinXR method encapsulates these machine details, including customizable XR interface elements, within their respective DT documents stored on a server. Two primary use cases illustrating TwinXR applications in the later chapter employed two machines: the overhead crane "Ilmatar" at AIIC, and a Universal Robots e-Series robot arm, UR5e. As described previously in Section 3.1.1, the crane serves as a digital twin-based experimental platform, completed with XR interfaces and OPC UA connectivity. Its metadata encompasses safe operational zones, and target positioning data. The UR5e robot arm, characterized by its flexibility and six joints, handles various tasks, controlled typically through the Robot Operating System (ROS). Its metadata details include speed, orientation range, and joint configurations.

The **DT document layer** serves as a critical intermediary, connecting the Smart Factory and XR application layers with bi-directional data flow. It hosts DT documents on servers, each uniquely mapped to a specific machine instance. These documents can also be universally applicable to multiple machines for shared XR applications, thanks to their uniform XR-related parameter structures. Customizable features in these documents influence XR applications, tailoring them to specific machine attributes and operational contexts. In practice, this work leverage the DT document standard established in [2], with formats of YAML and JSON, detailing a digital twin's metadata and characteristics. Besides the essential fields like a digital twin's name, identifier, and description, along with optional details such as manufacturer and product location, this work also extend the scope to incorporate XR-related features, divided into design aspects (like color and shape) and operational control elements (like target location). This enhancement ensures that XR applications are dynamically aligned with both aesthetic and functional specifications of the digital twins. This research utilizes Twinbase [6], an open-source, Git-based platform for managing and distributing DT documents. Twinbase harnesses GitHub's complimentary services, including repositories, Actions, and Pages. It facilitates the creation of new Twinbase instances and the addition of DT documents using templates. The platform's static website on GitHub Pages serves as the primary user interface, allowing for easy navigation and modification of digital twin and Twinbase entries. Each DT document includes a unique Twin ID, enabling the retrieval of corresponding documents through a Python client library. Additionally, to suit XR development needs, the work develops a Unity package with a C# script publicly available on GitHub [149], enhancing the project's integration with common XR development tools.

The **XR application layer** is composed of a DT-doc module and standard XR components. The DT-doc handler within this module facilitates two-way data exchange and format conversion between server-based DT documents and their local copies within the XR application. Essential to this process is the input of a Twin ID, which links the XR application to its corresponding DT document. The XR application includes modules like visualization and control as described previously in Section 3.1.2, each module with parameters that mirror those in the DT document. These parameters are adjustable in both directions, allowing for dynamic interaction and customization within the XR environment. This setup is termed "TwinXR-compatible", indicating its alignment with the TwinXR method. Existing technologies and platforms for development of this layer include 3D formats such as X3D, programming languages like Java and C#, libraries like OpenGL and WebGL, 3D modeling tools like Blender and 3ds Max, and game engines such as Unity and Unreal Engine. The XR applications are compatible with hardware ranging from VR devices like Meta Quest 2, MR devices like Microsoft HoloLens 2 and Varjo XR-3, to AR-capable Android and iOS mobile devices. Specifically, this project employs Unity for development and uses the Trimble XR10 with HoloLens 2 for implementation. Additionally, this work develops an open-source

Unity package [149] to simplify the establishment of the DT-doc module. The package comprises four C# scripts facilitating bi-directional data transfer and conversion between a DT document on Twinbase and its local version in an XR app. Key components are GlobalInstance.cs for global instance management, JsonReader.cs for retrieving and converting DT documents, JsonWriter.cs for updating DT documents on Twinbase, and SimpleJSON.cs, which defines the JSON format and provides parsing functions.

3.2.2 Development and utilization of TwinXR-compatible applications

This section outlines the development and utilization of TwinXR-compatible applications, detailing the process from application creation to user interaction. Initially, developers craft these applications through the creation and instantiation workflows; the applications are later initialized by users for interacting with DT documents in the reading and modifying workflows.

Figure 3.7 illustrates the development phase consisting of the creation and instantiation workflows. Overall, the creation workflow is executed once to set up both the DT document server and XR application frameworks; This foundational step allows developers to subsequently tailor DT documents on their server instances for new machinery or conditions, and adapt the XR application accordingly. Consisting steps of these two workflows are detailed below.

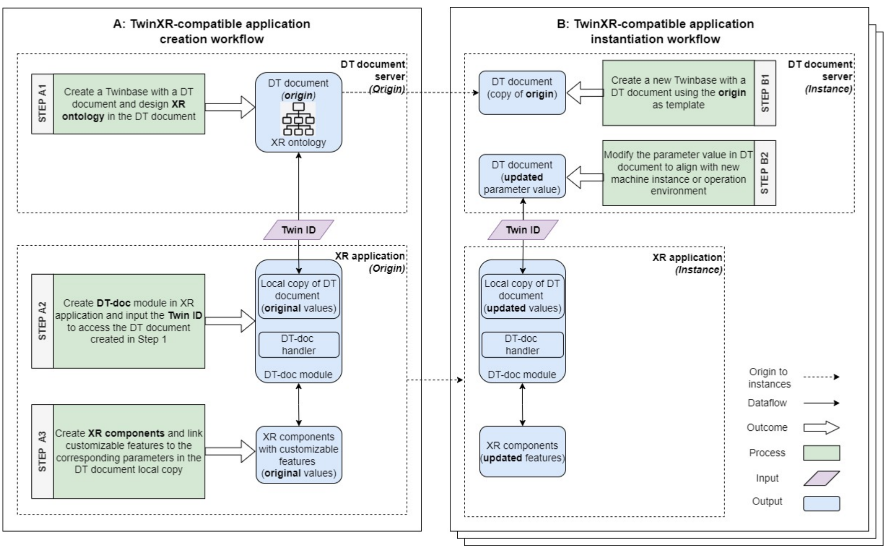


Figure 3.7. Development workflows of TwinXR-compatible applications (Publication II).

The creation workflow unfolds in three steps. Step A1 is conducted for the DT document server, while Steps A2 and A3 are for the XR application.

- Step A1: Create a server with a DT document, and define the XR ontology in the DT document. The outcomes of this step are the *origins* of the server and DT document.

- Step A2: Create a DT-doc module in the XR application *origin*, and input the Twin ID to access the DT document *origin* created in Step A1. The outcome of this step is a DT-doc module containing a reusable DT-doc handler. Through the Twin ID input, the DT-doc handler connects the XR application to the corresponding DT document *origin* created in Step A1, fetches and converts it into a local copy.

- Step A3: Create XR components and link customizable features to the corresponding parameters in the local DT document copy formed in Step A2. The outcomes of this step are the XR components with customizable features linked to parameters from the DT document *origin*. Hereby a complete data flow is established, from the DT document on the server, through its local copy in the XR application, to XR features.

The instantiation workflow consists of two steps, which are conducted solely for the server and DT document *instances*, while determining the corresponding XR application *instances*. Leveraging the *origins* of the server, DT document, and XR application, new developers can establish as many instances as needed for new machines or operating environments by repeating Steps B1 and B2.

- Step B1: Create a new server with a DT document, leveraging the server and DT document *origins* established in Step A1 as templates. The outcome of this step is a copy of the DT document *origin* on a new server.

- Step B2: Modify the parameter values of the DT document created in Step B1 to align them with the new machine instance or operating environment.

- Through the Twin ID of the new DT document, the XR application *origin* established in Steps A2 and A3 is automatically updated into a new instance: Firstly, the local copy of the DT document is updated with the new parameter values defined in Step B2; Consequently, the features of XR components are updated based on the updated parameters in the new local copy of the DT document *instance*.

The detailed technical workflows for utilizing a TwinXR-compatible application involve two main workflows. In the first workflow, the application customizes its settings by reading from a DT document. This begins with users entering the Twin ID upon launching the application, which enables the DT-doc module to retrieve the corresponding DT document. Subsequent modules within the XR environment then use the parameters from this local DT document copy for application customization, allowing users to commence their tailored application experience. The second process entails modifications to the DT document by the application during its use. Users interact with the XR interface to adjust the local DT document, which is then updated on the server by the DT-doc module, ensuring that the server's DT document reflects these changes. This allows for a seamless continuation of the XR application usage with updated configurations.

3.3 Industrial metaverse architecture

This section outlines the industrial metaverse architecture for smart factories, comprising the physical and metaverse spaces, as illustrated in Figure 3.8. The physical space includes tangible entities like machines, materials, personnel, and the environment, supported by infrastructure like sensors, actuators, and networks. The metaverse space mirrors this physical space with ten modules: coupling and data storage for data flow, semantic link for knowledge synchronization, XR interface for user interaction, and support functions including identifier, security, simulation model, computation, analysis, and AI. This section focuses on these key components and their interplay for data and knowledge management between physical and metaverse spaces.

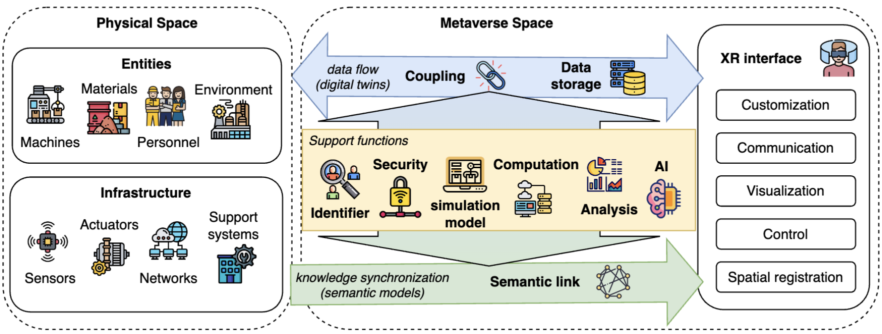


Figure 3.8. Proposed industrial metaverse architecture for smart factories (Publication III).

3.3.1 Physical space: entities and infrastructure

The physical space of the industrial metaverse is defined by several key **entities**: machines, materials, personnel, and the environment, each playing a vital role in industrial operations and forming the foundation for their digital counterparts in the metaverse. **Machines** include production equipment, robots, automation systems, integral to manufacturing and interconnected for smart processes. **Materials** encompass all items in the production chain, from raw inputs to final products, requiring efficient management for optimal production flow. **Personnel** represents the human workforce, central to Industry 5.0's human-centric approach, blending human skills with technology for enhanced system performance. Lastly, the **environment** of the factory, including its layout and conditions, is crucial for maintaining optimal production and minimizing disruptions. These elements together create a dynamic, data-rich environment essential for the functioning of the metaverse space.

The **infrastructure** of the physical space is crucial for seamless operations, linking the tangible world with the metaverse. This infrastructure, encompassing sensors, actuators, networks, and support systems, underpins manufacturing processes and bridges the physical with the digital. **Sensors** are key for real-time data collection, informing digital twins and decision-making in the metaverse. **Actuators** transform digital commands into physical actions. The **network** infrastructure is vital for data transmission. Lastly, **support systems** like power and data centers are fundamental for stability and efficiency.

3.3.2 Metaverse space: coupling and data storage for data flow

The coupling and data storage modules are essential for managing data flow in the metaverse. The coupling module facilitates data exchange between physical and metaverse space, while the data storage module maintains the metaverse's state, preserving data integrity and supporting continuous operations and analyses.

The **coupling** module establishes a bidirectional data connection between physical entities and their digital twins, enabling real-time synchronization through sensors, actuators, and network infrastructure, while ensuring data integrity via security and identifier modules. It facilitates *data acquisition* by capturing real-time states from physical sensors, *data transmission* through secure protocols like OPC UA, MQTT, and CoAP [136, 64], as well as *control and actuation* via actuators, translating digital commands into physical responses. Enhancing this module with a *data link* [2] provides centralized data access through an API gateway, streamlining the integration of diverse data for digital twin accuracy, and allowing adaptability to new IoT technologies and industrial shifts.

The **data storage** module oversees the retention and management of digital twin models representing machinery, materials, personnel, and environments, enabling two-way communication with the physical domain via the coupling module. These models are dynamically accessed, enhanced, and refined by simulation, computation, analysis, and AI modules, with data security and integrity bolstered by integrated security and identifier systems. Data storage employs various database types to meet distinct industrial metaverse needs, such as real-time databases for immediate updates, time-series databases for chronological data [115], and flexible NoSQL options like MongoDB for unstructured data [120]. Distributed databases ensure consistent data across networks [106], while graph databases are crucial for data relationships and ontologies [111]. The scalability required for the expanding metaverse data is addressed through cloud storage, which offers extensive resources, high availability, and robust backup features [59].

3.3.3 Metaverse space: semantic link module for knowledge synchronization

The **semantic link** module bridges the metaverse and physical spaces by encoding knowledge from physical entities of machines, materials, and personnels into semantic models. These models, structured according to standards like the Digital Twin Definition Language (DTDL) [90], the Web of Things Thing Description (WoTTD) [68], and the Asset Administration Shell (AAS) [109], use linked data formats such as JavaScript Object Notation for Linked Data (JSON-LD) [142] for machine-readable data representation. This setup facilitates linking to external data sources and forms a global data framework, with semantic queries, like SPARQL Protocol and Resource Description Framework (RDF), shortly as SPARQL, enabling precise data extraction. The module's effectiveness hinges on domain ontologies, which standardize knowledge representation using established ontologies like schema.org [128], the Smart Applications REFerence (SAREF) [127], and GS1 Web Vocabulary [51], alongside customized ontologies developed in collaboration with industry experts. This approach allows for the integration of diverse data sources, enhancing the industrial metaverse's connectivity with existing industrial systems.

3.3.4 Metaverse space: XR interface module for user interaction

The **XR interface** module serves as a vital link for user interaction with digital twins within the industrial metaverse, offering immersive experiences that mirror real-world interactions. The module facilitates user navigation, manipulation, and communication in the metaverse, blending digital and physical spaces seamlessly. Integrating VR, AR, and MR tailors experiences to each technology's strengths: VR's total immersion is ideal for risk-free training and product design in simulated environments; AR and MR overlay digital information onto the real world for tasks like maintenance and inspections, requiring digital twins to provide real-time, relevant data. The XR interface comprises five essential functions as detailed in Section 3.1.2 and 3.2.1: *communication*, for data exchange between the XR interface and digital twins; *visualization*, to accurately display digital twin information and analytics; *control*, allowing users to interact with the metaverse via intuitive inputs; *spatial registration*, ensuring virtual content aligns with the physical world; and *customization*, adapting the interface to user needs and factory conditions based on semantic model queries. This framework enhances the XR interface's adaptability and user experience, catering to individual preferences and evolving industrial environments.

3.3.5 Metaverse space: support functions

In the metaverse space, six essential modules, namely, identifier, security, simulation model, computation, analysis, and AI, form the core support functions. These modules collectively ensure accurate identity verification, robust data security, realistic simulations, efficient processing, insightful analytics, and smart decision-making, creating a dynamic and secure virtual environment that integrates seamlessly with the physical space.

The **identifier** module assigns unique and persistent identifiers to each digital twin, enhancing their discoverability and interaction within the industrial metaverse. This system not only simplifies data exchanges but also ensures that only authorized users can access and modify specific digital twin models. It encompasses the creation, resolution, and management of these identifiers, alongside their integration with the metaverse's broader architecture, guaranteeing consistent entity recognition and accessibility. The work proposes employing Uniform Resource Identifiers (URIs) [12] for reliable digital resource referencing, blockchain technology [43] for secure and immutable records, and Decentralized Identifiers (DIDs) [117] for users' autonomy over their digital identities, crucial for navigating the extensive metaverse landscape.

The **security** module plays a crucial role in maintaining the integrity of the industrial metaverse, particularly in protecting digital twin data. It employs the Advanced Encryption Standard (AES) like AES-256 encryption [55] for stored data and the Transport Layer Security (TLS) protocols with Secure Hashing Algorithms (SHAs) like SHA-256 [122] for data in transit, ensuring robust encryption. User and system identities are verified through multi-factor authentication and digital certificates [71], while access control is managed via Role-Based Access Control (RBAC) [39] or Attribute-Based Access Control (ABAC) systems [60] to define user permissions. The network is secured by firewalls with Stateful or Deep Packet Inspection [45] and monitored by intrusion detection systems like Snort [118] and OSSEC [26]. To address the unique security challenges posed by human integration, the module adopts differential privacy and homomorphic encryption, emphasizing a "secure by design" approach [13] and the development of intuitive, fail-safe XR interfaces.

The **simulation model** module forms digital twins utilizing a range of modeling techniques to encapsulate the physical attributes, behaviors, and graphical representations of their real-world counterparts. This module enables the creation of high-fidelity digital twins, which are dynamically updated through a feedback loop with the data storage module, reflecting changes and outputs from the simulation models. The choice of modeling technique depends on the specific requirements of the physical system being modeled: mathematical modeling for precise system behaviors [95], 3D modeling for detailed visual replicas via Computer-Aided Design (CAD) [155], Finite Element Analysis (FEA) modeling for responses to physical forces [58], or system dynamics for understanding complex system behaviors over time [129]. Ensuring the accuracy and validation of these simulation models against real-world observations is vital for maintaining the reliability and effectiveness of the digital twins they represent.

The **computation** module processes and transforms digital twin data, with a focus on spatial computing to align the physical and digital spaces [153, 107], integrating with the XR interface module for intuitive visualizations of spatial data. It incorporates indoor positioning technologies like Wi-Fi [154], Bluetooth [38], ultra wideband (UWB) [125], markers [**?**], object detection [**?**], or spatial anchors [54], for accurate spatial data collection. The work proposes leveraging an "edge-cloud continuum" approach [93], combining edge computing's immediate response capabilities [31] with cloud computing's extensive processing power [20]. The module should also utilize parallel and distributed computing to optimize resource use and accelerate processing in time-critical metaverse applications.

The **analysis** module processes digital twin data for actionable insights, employing descriptive, predictive, and prescriptive analytics to assess system states, forecast future scenarios, and suggest optimal actions. The choice of analysis techniques is tailored to the data characteristics and specific application needs [144], including time-series for temporal trends [87], clustering for data segmentation [11], and anomaly detection for identifying irregularities [143]. Ensuring data quality through cleansing and validation is crucial for reliable analyses. Moreover, the integration of this module with others, such as simulation models for scenario modeling [160], enhances decision-making and strategic planning, aligning with a human-centric approach.

The **AI** module harnesses digital twin data to facilitate smart decision-making, improving the industrial metaverse's efficiency and fostering human-machine collaboration. It utilizes machine learning and deep learning to discern patterns, forecast outcomes, and adapt through experience, with reinforcement learning fine-tuning decisions in dynamic environments, particularly in robotic applications [157]. Integrating natural language processing and computer vision enhances user interaction with AI systems, supporting a human-centric approach [158]. Additionally, generative AI and large language models can create contextual content for XR users, enriching the metaverse experience [80]. This integration upholds human-in-the-loop principles [167], augmenting human expertise and ensuring AI transparency and accountability.

3.3.6 Data flow and knowledge synchronization

The proposed industrial metaverse architecture facilitates both data flow and knowledge synchronization between the physical and metaverse spaces. At the heart of this system's information management and integration are two key ontological elements: the Terminology box (T-box) and the Assertion box (A-box). As illustrated in Figure 3.9, the T-box sets up the ontological structure and conceptual connections within semantic models, crucial for harmonizing knowledge, while the A-box contains actual data or instances, filling out the digital twin models vital for data circulation. Their bidirectional interaction ensures that both the schema provided by the T-box and the instances from the A-box continually inform and refine each other, keeping the system's state consistent and integrated.

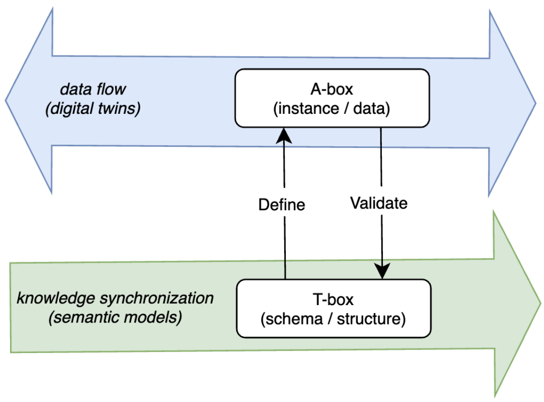


Figure 3.9. Overview of data flow and knowledge synchronization with T-box and A-box in the industrial metaverse (Publication III).

The data flow process ensures fluid interaction between the physical world and the metaverse. This system hinges on bi-directional data exchange across key modules, with the A-box playing a critical role by housing actual data instances crucial for the real-time update of digital twins. As depicted in Figure 3.10, data from physical sources is collected by sensors and channeled through a central coupling module, serving as the metaverse gateway. This module, alongside the identifier and security modules, safeguards data integrity and manages access. Control commands from the metaverse are then relayed back to physical actuators, enabling precise adjustments in the physical domain based on digital twin insights. Additionally, the XR interface module visualizes this data, creating an immersive environment for users, while also facilitating the input of control commands back into the system for ongoing interaction and control.

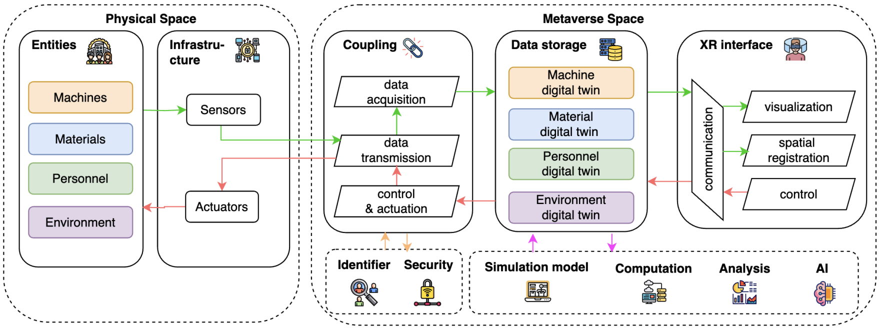


Figure 3.10. Data flow process in the proposed industrial metaverse architecture (Publication III).

The knowledge synchronization process translates real-world data into structured ontologies that facilitate interactions between the physical space and the metaverse. This process is primarily governed by the T-box, which outlines the ontological structure and conceptual linkages within semantic models. As illustrated in Figure 3.11, the process starts with ontology modeling of physical entities, extending this structured knowledge through semantic models in the metaverse. This knowledge then informs the XR interface, enabling customization based on ontology-based queries, which refine data into useful insights on machine statuses and environmental conditions. The XR interface leverages this knowledge to enhance visualization accuracy, ensure precise control, maintain spatial registration, and streamline communication within the virtual environment, aligning the XR application with the operational context.

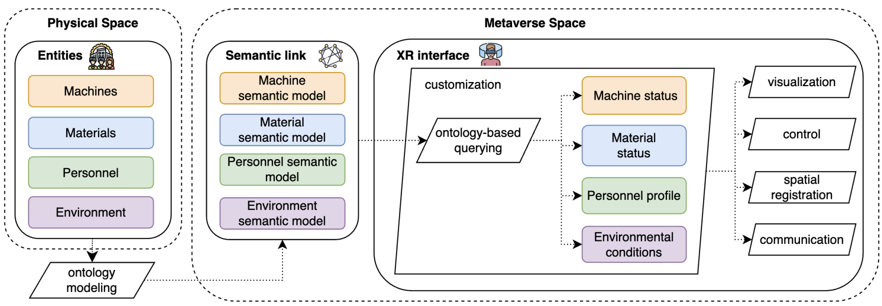


Figure 3.11. Knowledge synchronization process in the proposed industrial metaverse architecture (Publication III).

4. Results

This chapter presents the results of applying the aforementioned methods and materials in industrial settings. It begins by detailing the control accuracy of the MR application operating a digital twin-based crane over 20 measurements. The chapter then showcases the practical application of the TwinXR method in a smart factory context, highlighting its use in operating standard industrial devices like overhead cranes and robot arms. The implementation process, involving identification of customizable XR features, the setup of a Twinbase server with DT documents, and the development of TwinXR-compatible XR applications, is thoroughly explored. The chapter concludes with a case study on in-plant material flow tracking for exemplifying the industrial metaverse architecture's capabilities in enhancing industrial workflows.

4.1 Control accuracy measurement result for the mixed reality application

Following the protocol defined in Section 3.1.3, the work conducts the measurement on control accuracy of the developed MR application and notes two observations: There are instances of hologram displacement, including the bounding box and target holograms, during the registration phase and while manually maneuvering the crane; Aligning the holograms with their physical counterparts proves challenging, particularly during the registration of the bounding box with the image target and in aligning the crane hook with the target holograms during manual operation.

From these measurements, the work gathers the crane's actual position data across 20 tests and the designated positions for two targets, each comprising values for three directions of movement, corresponding to the components of the hoist, bridge, and trolley. The work then visualizes the crane's positions from these 20 tests as histograms in Figure 4.1 to depict the distribution of data, with the x-axis showing positions in meters and the y-axis indicating the frequency of positions within specific ranges.

The target positions are indicated on these histograms by vertical dashed lines. These visualizations highlight the variance between intended target positions and the crane's actual positions across different tests, while the errors are within the range of 10 cm along any of the three moving directions.

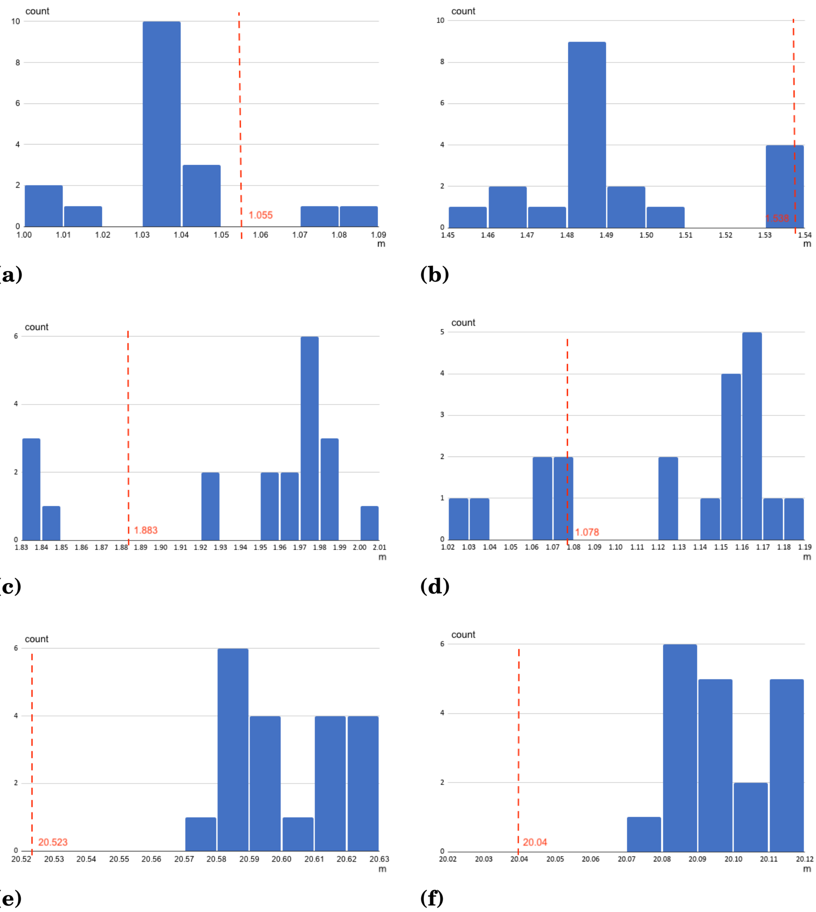


Figure 4.1. Histograms of 20 measurements, representing the actual crane position of each moving subsystem per each of the two selected targets, with the actual target position marked as vertical dashed lines (Publication I): (**a**) Target 1 — Hoist (Y); (**b**) Target 2 — Hoist (Y); (**c**) Target 1 — Trolley (X); (**d**) Target 2 — Trolley (X); (**e**) Target 1 — Bridge (Z); (**f**) Target 2 — Bridge (Z).

4.2 TwinXR implementation for industrial cranes and robot arms

The work applies TwinXR method in industrial settings through a proof-of-concept implementation for operating common Smart Factory devices like overhead cranes and robot arms. The source code developed for the implementation is publicly available in the GitHub repositories linked to the customized Twinbase [150] and the Unity MR project [148]. The process entails defining the XR ontology in DT documents, setting up a Twinbase server with these documents, and creating TwinXR-compatible XR applications for operational scenarios. As elaborated in Section 3.2.1, the implementation uses the "Ilmatar" crane and the Universal Robots e-Series robot, UR5e as reference models. The architecture of this setup includes a Twinbase server hosting the DT documents and an MR application primarily running on the Trimble XR10 with HoloLens 2, while also adaptable to other devices like Meta Quest 2. Users interact with these applications by scanning QR codes of the Twin IDs, reading DT documents from the server, customizing applications according to parameters from these documents, and updating DT documents through the application. Figure 4.2 illustrate the architectural setup for TwinXR method implementation in the context of crane operations. The approach adopted for the robot arm application mirrors this architecture, applying the same principles and structure as used in the crane scenario.

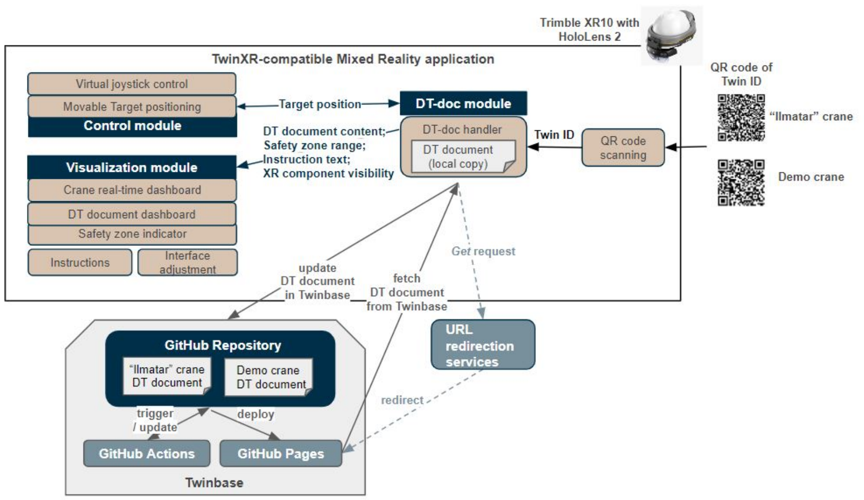


Figure 4.2. Architecture of a TwinXR-compatible MR application for crane operation (Publication II).

The implementation starts with identification of customizable XR features and their definitions in DT documents. Table 4.1 and 4.2 list XR-related terms for the crane's and robot arm's DT documents, categorizing these terms into design and control types. This customization tailors the applications to certain machine specifications and operating environments, facilitating ease of use and safety. The complete descriptions of terms in the DT document can be found in the GitHub repository [150].

The implementation of Twinbase servers and the creation of DT documents for the crane and robot arm uses a provided template which includes a GitHub repository, GitHub Actions, and GitHub Pages, detailed in [6].

Table 4.1. Customizable XR features in the crane's DT documents (Publication II).

Category	Term	Description	Format
design	targetColor	The color of the target hologram, by default yellow	string
design	targetShape	The shape of the target hologram, by default sphere	string
design	targetSize	The size of the target hologram (cm), by default 20 (diameter)	float
design	targetOpacity	The opacity of the target holograms (%), by default 70	float
design	dashboardPosition	The position of the dashboard center with regard to the user (m), by default (1, 0, 0)	array of three floats
design	dashboardScale	The scale of the dashboard, by default 1	float
design	dashboardAngle	The angle between the dashboard and the plane that is vertical to the user's sight line, by default 0	float
design	visibilityUI - dashboard	Whether the dashboard UI is visible, by default true	boolean
design	visibilityUI - target	Whether the target UI is visible, by default true	boolean
design	visibilityUI - instruction	Whether the instruction UI is visible, by default true	boolean
design	instruction	Instruction text about using the XR application	string
design	safetyZoneDisplayStyle	The hologram style of the safety zone indicator, either "fill" or "outline", by default "outline"	string
control	markerLocationBridge	The location of the registration marker in the crane's bridge dimension (cm)	float
control	markerLocationTrolley	The location of the registration marker in crane's trolley dimension (cm)	float
control	markerLocationHoist	The location of the registration marker in crane's hoist dimension (cm)	float
control	safetyZoneHoist	The range of the safety zone in crane's hoist dimension (cm)	array of two floats
control	safetyZoneTrolley	The range of the safety zone in crane's trolley dimension (cm)	array of two floats
control	safetyZoneBridge	The range of the safety zone in crane's bridge dimension (cm)	array of two floats
control	targetLocationHoist	The location of the target in crane's hoist dimension (cm)	float
control	targetLocationTrolley	The location of the target in crane's trolley dimension (cm)	float
control	targetLocationBridge	The location of the target in crane's bridge dimension (cm)	float

The repository houses DT documents and related files that are updated and distributed via GitHub Pages. To manage Twin IDs, the work uses dtid.org's URL redirection service. In the crane case, the Twinbase server hosts DT documents of both the "Ilmatar" crane and a demo crane that is of the same type as the "Ilmatar" but located in a different operating environment, thus with different safety zone, target location, etc.

Finally, the work develops two MR applications compatible with the

Table 4.2. Customizable XR features in the robot arm's DT documents (Publication II).

Category	Term	Description	Format
design	dashboardPosition	The position of the dashboard center with regard to the user (m), by default (1, 0, 0)	array of three floats
design	dashboardScale	The scale of the dashboard, by default 1	float
design	dashboardAngle	The angle between the dashboard and the plane that is vertical to the user's sight line, by default 0	float
design	visibilityUI - dashboard	Whether the dashboard UI is visible, by default true	boolean
design	visibilityUI - instruction	Whether the instruction UI is visible, by default true	boolean
design	instruction	Instruction text about using the XR application	string
design	safetyZoneDisplayStyle	The hologram style of the safety zone indicator, either "fill" or "outline", by default "outline"	string
control	markerLocationX	The location of the registration marker in the pre-defined X dimension (cm)	float
control	markerLocationY	The location of the registration marker in the pre-defined Y dimension (cm)	float
control	markerLocationZ	The location of the registration marker in the pre-defined Z dimension (cm)	float
control	safetyZoneX	The range of the safety zone in the pre-defined X dimension (cm)	array of two floats
control	safetyZoneY	The range of the safety zone in the pre-defined Y dimension (cm)	array of two floats
control	safetyZoneZ	The range of the safety zone in the pre-defined Z dimension (cm)	array of two floats
control	offsetOrientationJoint	The offset orientation of a joint (degree)	float
control	speedRangeJoint	The speed range of a joint (degree per second)	array of two floats
control	orientationRangeJoint	The orientation range of a joint (degree)	array of two floats

TwinXR method, named "HoloCrane" and "HoloRobot", as shown in Figure 4.3 and 4.4 respectively. "HoloCrane" allows users to control and monitor a virtual crane, whereas "HoloRobot" provides the capability to view and interact with a robot arm's status, including its connection to external software like ROS. Both applications feature a virtual dashboard that displays real-time machine data and DT document content, including crucial information about the machines and operational parameters. They also share functionalities like a safety zone indicator, instructional guides, interface customization, and QR code scanning for Twin ID input, which links the application to the corresponding DT document on the Twinbase server. The architecture of these applications includes a DT-doc module for data handling, a control module for interactive operations, and a visualization module for displaying information and interface options.

In summary, the TwinXR method is applied in a proof-of-concept implementation for industrial cranes and robot arms, involving the setup of a Twinbase server with DT documents and the development of TwinXR-

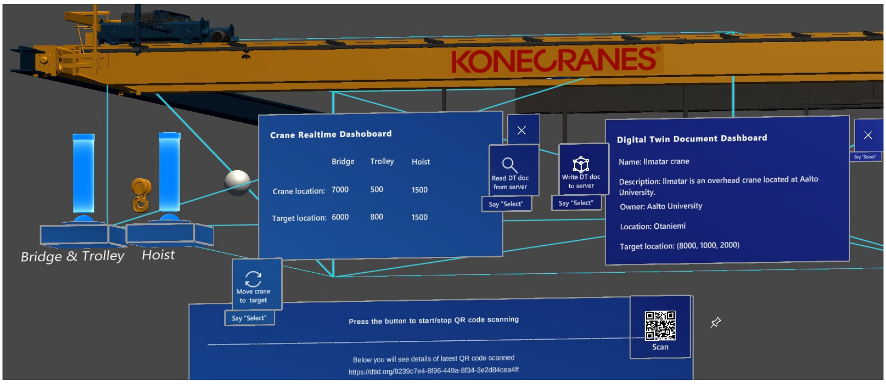


Figure 4.3. MR application “HoloCrane” on Unity desktop view (Publication II).

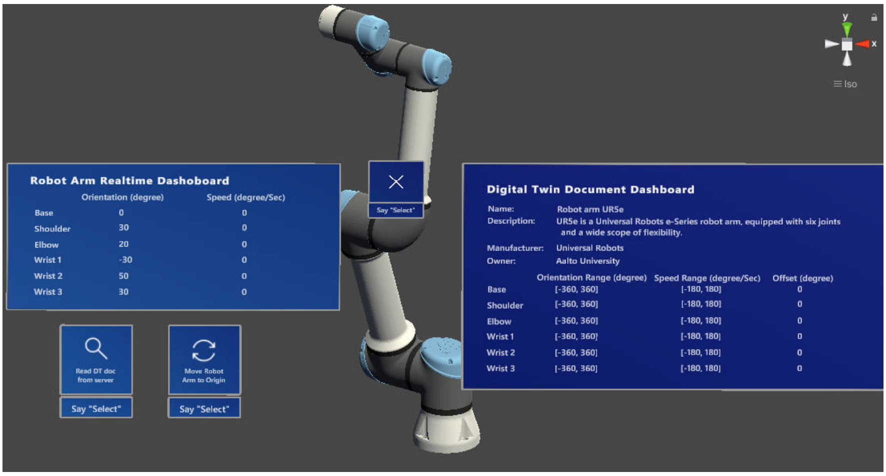


Figure 4.4. MR application “HoloRobot” on Unity desktop view (Publication II).

compatible XR applications for operational use. Utilizing “Ilmatar” crane and UR5e robot as models, the implementation features customizable XR applications that allows users to interact with machinery through scanning QR codes and customizing applications based on DT documents.

4.3 Industrial metaverse case study: in-plant material flow tracking

The work exemplifies the effectiveness of the industrial metaverse architecture through a case study of in-plant material flow tracking. Figure 4.5 illustrates the multifaceted physical space setup of this case study, the AIIC, comprising essential components like materials, transportation systems, tracking mechanisms, human operators, and the overall environment. Central to the operation is the overhead crane, as detailed in Section 3.1.1, utilized as the primary transportation device, alongside wooden pallets representing the materials in transit. A crucial aspect of this setup is the role of a human operator overseeing and steering the material flow. To augment the precision of the tracking process, the work employs a UWB indoor positioning system, equipped with beacon devices. These components are integrated into the AIIC's infrastructure, which includes a wireless network for the crane and a private lab-wide 5G network.

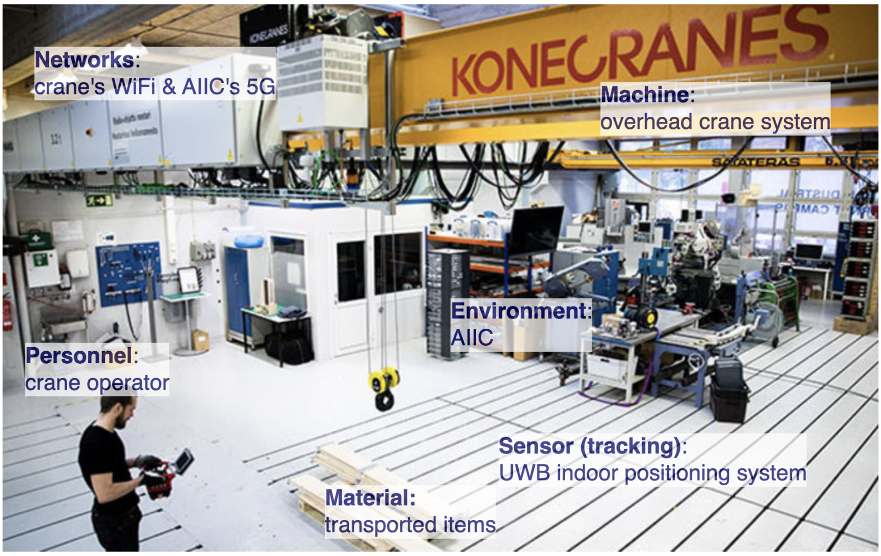


Figure 4.5. Physical space setup of the industrial metaverse case study at AIIC (Publication III).

The metaverse space in the case study covers four key modules: the coupling module for data flow, the semantic link for knowledge synchronization, the XR interface module for user interaction, and the simulation module as a support function.

The **coupling** module handles data acquisition, transmission, control, and actuation. Focusing on our crane example, a Programmable Logic Controller (PLC) gathers data from crane sensors and actuators, which is then made accessible through an OPC UA server, acting as the primary interface. Data transmission leverages various communication middleware, including OPC UA-GraphQL, OPC UA-MQTT wrappers, and an OPC UA-Unity client, detailed in prior research [163]. These solutions enable interaction between the OPC UA server and different client systems, crucial for modules like the XR interface. Bi-directional data flow allows commands from XR interface module to control the crane or its simulated version. Additionally, the module integrates real-time location data from the UWB indoor positioning system, ensuring accurate mirroring of material locations and movements in the metaverse, aiding in simultaneous real-world and metaverse tracking.

The **semantic link** module in our architecture utilizes the Industrial

PROduction workflow ontologies (InPro), previously introduced in [164]. InPro integrates production process information, suitable for scenarios like material flow tracking, by assimilating both structured and unstructured data from varied sources including real-time OPC UA server feeds and systems like Enterprise Resource Planning (ERP), Human Resource Management System (HRMS), Manufacturing Execution System (MES), Warehouse Management System (WMS), and Product Lifecycle Management (PLM). The InPro ontology is composed of seven modules: *Entities*, *Agents*, *Machines*, *Materials*, *Methods*, *Measurements*, and *Production Processes*. This ontology is stored in a semantic graph database, GraphDB, allowing information retrieval through SPARQL queries.

The **XR interface** module facilitates interactive user experiences for material flow management in the industrial metaverse. For remote activities, VR provides an immersive virtual environment, allowing operators to monitor and control material flows from afar. An example is using VR headsets to oversee factory operations and guide cranes in a virtual setup mirroring the actual space, as depicted in Figure 4.6. Alternatively, the AR/MR interface, designed for on-site use, overlays critical information onto the physical environment through devices like smart glasses. This setup, exemplified by users wearing Microsoft HoloLens headsets, integrates real-time data for managing crane operations and material handling, as demonstrated in Figure 4.7. Both VR and AR/MR applications incorporate synchronized data overlays, which are derived from UWB and diverse industrial systems, integrated by the InPro, and transmitted through coupling mechanisms, providing users with immediate details about materials' properties, status, and location.

The **simulation model** module uses CAD models created with Siemens PLM software NX to represent the crane, materials, and their environment. These models are then converted into interactive simulations that incorporate the crane and materials within their operational setting using the Unity engine and the ROS Gazebo simulator. The Unity-based simulations form the basis for XR scenes, enabling immersive VR experiences as in [163] or AR/MR spatial registration as in Publication I. Simultaneously, ROS-Gazebo simulations are enhanced with virtual sensors like inertial measurement units (IMUs) and provide realistic behavior simulations, aiding in virtual commissioning, especially when combined with other support functions of the metaverse space like the computation, analysis, or AI modules.

In summary, the industrial metaverse case study on in-plant material flow tracking demonstrates the integration of physical elements like cranes with advanced UWB tracking within a metaverse framework, featuring four key modules' implementation: The coupling module, through PLCs and an OPC UA server, ensures real-time data capture from crane sensors for accurate tracking and control; The semantic link module leverages

Figure 4.6. VR application for remote crane operation and material flow tracking (Publication III).

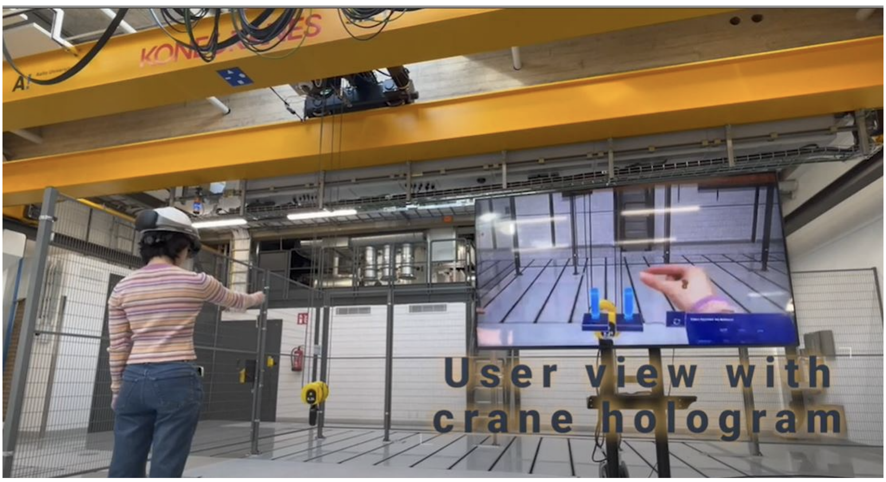


Figure 4.7. AR/MR application for on-site crane operation and material flow tracking (Publication III).

InPro ontologies to synchronize diverse data systems, enabling a unified knowledge base; The XR interface module enriches user interaction with immersive VR for remote oversight and AR/MR for direct on-site management; Lastly, the simulation model module employs CAD, Unity, and ROS-based simulations to replicate the operational environment.

5. Discussion

This chapter provides an in-depth evaluation and outlines the merits, challenges, and future directions for three integral components in Industry 5.0 applications: the MR application for digital twin-based cranes, the TwinXR method, and the industrial metaverse architecture. It scrutinizes the current state of MR application in crane operations and proposes enhancements in assessing control accuracy, usability, safety features, latency and responsiveness. The TwinXR method's evaluation focuses on its efficacy in integrating digital twins with XR, emphasizing its merits in enhancing efficient and scalable XR development, as well as data interchange and system interoperation with digital twins across various industrial scenarios. Future enhancements for TwinXR include aligning with Semantic Web technologies and developing broader, factory-level applications. Lastly, the evaluation of the industrial metaverse architecture highlights its role in unifying physical and digital factory spaces for industrial applications, focusing on its data flow and knowledge synchronization capabilities, alongside its validity demonstrated by a case study. The chapter also identifies future challenges and research opportunities for the industrial metaverse, including comprehensive validation, customization and personalization, multi-user interaction, real-world data challenges, human factors and human-centric design, environmental impact, as well as ethical and regulatory considerations. Finally, the discussion outlines the overall scientific and practical implications of the thesis.

5.1 Evaluation of the mixed reality application for digital twin-based crane

This section discusses the merits of the MR application in operating digital twin-based cranes through comparison with existing literature and commercial systems. Key areas of future research are discussed, including control accuracy, usability research, safety features, as well as latency and responsiveness.

5.1.1 Merits of this work

This work advances the application of MR interfaces in operating digital twin-based industrial systems, specifically focusing on a novel MR interface for a digital twin-based overhead crane platform.

The MR application, compatible with the Microsoft HoloLens 1, integrates various software tools and development kits including Unity, MRTK, PTC Vuforia SDK, and RestSharp API, alongside the crane's own software systems like its OPC UA interface, the GraphQL wrapper, and connectivity solutions. The application comprises four main modules: an interaction module for crane navigation, a visualization module displaying crane status and user instructions, a registration module enhancing operational flexibility with spatial tracking, and a communication module facilitating real-time, two-way data exchanges. Additionally, the work establishes a detailed protocol for measuring the MR application's control accuracy over the crane, implementing 20 measurements in the fixed target control mode. Analysis of these measurements shows that deviations between target and actual crane positions stay within a 10-cm range across all axes, which is acceptable given the crane's operational scope and logistics applications.

This initial exploration into the industrial metaverse, through the development and application of this MR interface, sets a foundational benchmark for evaluating the effectiveness and precision of XR technologies in real-world industrial settings. Unlike existing solutions that predominantly feature unidirectional data flows, this MR application facilitates interactive and responsive operations. This enhanced interactivity is directly aligned with the research aims to address the substantial gaps in dynamic integration of XR systems and digital twins within industrial settings and robust evaluation on control accuracy.

5.1.2 Challenges and future works

This section discusses the challenges and future directions evolved from this work. While the application demonstrates sufficient accuracy for general logistics operations, precision tasks demand further refinement. The incorporation of user-centered design principles in future usability studies, the integration of advanced safety features, and a comprehensive assessment of control latency and responsiveness are identified as critical pathways for evolving XR applications for digital twin-based systems to better meet industrial needs and enhance user experience.

Control accuracy: The study's control accuracy measurements reveal that discrepancies between intended and actual crane positions remain within a 10 cm range in all directions. This degree of accuracy is adequate for general crane operations in logistics, but insufficient for precision-intensive tasks like heavy shrinking fit lift operations, which require accuracy below 0.5 mm, as noted in [137]. Observed biases in control accuracy across different dimensions suggest potential improvements through adjustments in the spatial transformation calibration process. The reliability of the current registration and tracking methods is variable, often resulting in hologram displacement. Future enhancements could involve integrating multiple planar markers for more robust registration and tracking, as discussed in [151, 166], and potentially employing 3D model-based tracking techniques for more precise and reliable performance, similar to the methods highlighted in [10, 121, 114]. These advancements could lead to significant reductions in error, enhancing both the effectiveness and mobility of the application.

Usability research: The work achieves a proof-of-concept stage, primarily focusing on the technical viability of industrial MR for digital twin services, underscored by control accuracy evaluations. However, HMI design also emphasizes user integration within cyber-physical systems, as outlined in [47]. Recognizing the importance of user studies, future work aims to assess interface usability via the System Usability Scale [16] and workload using the NASA Task Load Index [53], following methodologies similar to those in [156, 113]. These evaluations will involve substantial user participation to yield statistically significant results.

Safety features: Incorporating a vast array of digital twin data in an intuitive way poses a challenge for HMI development, especially when prioritizing safety and situational awareness, a concept highlighted in [169]. MR technologies enhance interaction with digital twin data, though their impact on system safety is a consideration. This work integrates safety features in the MR interface, such as spatial mapping for enhanced awareness and color-changing feedback for target selection. Future enhancements could include more safety features and systematic evaluations of MR's impact on operator performance and situational awareness, similar to frameworks like [49]. Additionally, adapting the dead man's switch to a portable, wearable format could enhance safety and usability in MR environments.

Latency and responsiveness: While the interface's control accuracy is assessed, focusing solely on spatial performance, future studies should incorporate control latency to provide a comprehensive quantitative evaluation. Control latency could be defined variously, such as the duration from an interaction (like selecting a hologram) to crane movement, or the time difference between sending an HTTP request and receiving a response from the server. The network latency can be measured with throughput and handover rates through field trials as in [131]. These different interpretations of control latency necessitate unique evaluation methods and data collection processes, as discussed in [62]. Latency effects on Quality of Experience should also be further investigated as in [17, 18]. Additionally, future research could include time-related plots to visually represent the responsiveness of crane operations via the MR application, as suggested in [134].

5.2 Evaluation of the TwinXR method

This section evaluates the TwinXR method, showcasing its merits in effectively integrating digital twins with XR technologies across various industrial applications, while highlighting the method's broad applicability. Looking ahead, the discussion outlines potential advancements for TwinXR, suggesting a path towards more integrated and expansive solutions.

5.2.1 Merits of this work

The TwinXR method tackles the challenge of integrating digital twins with XR technologies, facilitating mutual enhancements that drive Industry 5.0 towards the Metaverse. This method enables digital twins and XR to act as enablers for one another, enhancing efficiency, scalability, interchangeability, and interoperability. Through the TwinXR method, digital twins help optimize and scale XR application development, while TwinXR-compatible applications showcase the capabilities of digital twins in terms of data exchange and system interoperability. The three-folded merits of the TwinXR method are elaborated as follows.

Efficient and scalable XR application development: The TwinXR method utilizes DT documents, which facilitate the centralized development of an initial XR application, known as the origin. This setup allows for subsequent local modifications of the origin into application instances without the need for extensive XR development knowledge. This approach not only streamlines the development process requiring expertise in XR development tools like Unity, but also simplifies the adaptation of applications to meet different operational needs through straightforward modifications of DT documents. Additionally, the work introduces a publicly available Unity package [149] that simplifies the integration of XR applications with DT documents, enhancing the ease of application development using the TwinXR method. The architecture of TwinXR-compatible applications supports independent modifications of each component, enhancing the robustness and flexibility of the overall system. The use of a Git-based system for hosting DT documents further improves the discoverability and reusability of these applications, enabling new developers to easily adopt and adapt pre-existing solutions. Contrasting with traditional XR solutions that are often designed for specific, singular purposes, as presented in [46, 57, 21], the TwinXR method facilitates the creation of adaptable, generic XR applications suitable for a wide range of industrial applications and user roles, from designers to operators. This adaptability is primarily driven by the flexibility allowed by the DT documents, which define the operational parameters for new machines and environments.

Data interchange and system interoperation with digital twins: The TwinXR method enhances the interoperability and interchangeability of digital twin systems, positioning digital twins as a crucial intermediary for data integration and exchange among various machines and their associated applications. This capability demonstrates the potential of digital twins to facilitate seamless interaction and operational synergy across different systems, a research gap highlighted by [27] with its systematic literature review regarding data management of digital twins. By utilizing a shared ontology in DT documents, the TwinXR method ensures a consistent flow of knowledge across different domains, enabling various applications connected to a single machine to utilize and share specific data fields. This shared data architecture allows TwinXR-compatible applications to communicate effectively, enhancing collaboration and operational coherence between machines and applications. Information-oriented digital twins serve as a bridge to connect disparate data silos, enhancing visibility and transparency across manufacturing processes. This connectivity fosters collaboration and drives efficiency improvements, supporting better decision-making within a Smart Factory environment. The TwinXR method supports bi-directional data flows, allowing users to interact with and modify DT documents directly through XR applications, which facilitates intuitive and user-friendly management of information. This approach not only streamlines operations but also leverages modern interfaces for better data handling and system management.

Advantages of using TwinXR in the crane and robot arm cases: TwinXR demonstrates its utility in handling diverse industrial machines like cranes and robot arms by centralizing XR application development. The method employs DT documents to standardize data fields such as machine names, locations, and movements, which simplifies adapting applications to different machines without redoing the XR development for each variant or update. This streamlined approach allows for the quick adjustment of XR applications by merely updating digital twin descriptions, thus accommodating changes like different operating environments or updates in machine specifications. The centralized management of these documents on the Twinbase server facilitates the reuse of XR solutions across multiple types of machines, enhancing scalability and efficiency. Moreover, TwinXR enables stakeholders without deep technical expertise in XR development to make necessary adjustments easily, promoting flexible and rapid adaptation to changing industrial needs. This capability ensures that XR applications are both versatile and practical for widespread industrial use, aligning with the dynamic requirements of a Smart Factory.

Overall, the TwinXR method is a versatile approach designed to enhance the integration of digital twins and XR in industrial applications. Its generality is reflected in its three-layer architecture comprising Smart Factory, DT document, and XR application layers: In the Smart Factory layer, it accommodates a range of physical machines connected with digital twins and XR interfaces, making it suitable for various industrial settings; The DT document layer, with its common data ontology, enables the management of diverse machine data, making it widely applicable; The XR application layer's composable and modular architecture further underscores the method's adaptability across different XR development tools and platforms. While specific use cases like cranes and robot arms are demonstrated, the TwinXR method's structure and processes are intended to be generally applicable, allowing for broad application across different industrial contexts. However, it is noted that in static or specific-use scenarios, traditional XR development methods like [46, 57, 21] might be more cost-effective than applying the more flexible but complex TwinXR method.

5.2.2 Challenges and future works

The TwinXR method significantly enhances interoperability among machines, DT documents, and XR applications. Currently, the method relies on the unified data structures of DT documents for feature mapping between XR components, which confines XR application to only be adaptable for machine types they were originally designed for. To elevate interoperability further, the following advancements are proposed: adopting Semantic Web and Knowledge Graph technologies, and developing factory-level TwinXR-compatible applications.

Adopting Semantic Web and Knowledge Graph: The proposed advancements include aligning the TwinXR method with the Semantic Web to utilize machine-readable data, enhancing the widespread applicability of DT documents. While Twinbase currently employs YAML for DT documents due to its user-friendliness, transitioning to a standardized linked data format like JSON-LD [141] is recommended to facilitate better integration and standardization. Furthermore, incorporating Knowledge Graphs principles [37], which employ graph-structured data models, will improve the integration and accessibility of data across different machines, streamlining the adaptation of TwinXR-compatible applications to new settings with minimal manual intervention.

Developing factory- level TwinXR-compatible applications: Scaling up to a factory level involves linking a single XR application to a factory digital twin that governs multiple machine digital twins. This integration requires careful management of DT documents to ensure that environmental parameters like safety zones are defined once and accessible by all relevant machine digital twins. A comprehensive semantic framework is necessary for seamless information exchange across various applications within the factory setup. Adopting the Smart Factory Web concepts [66] [56] and integrating factory-level TwinXR applications into cross-site manufacturing scenarios will be crucial. These efforts should leverage existing industrial frameworks and reference architectures like the one proposed by [152] to facilitate open marketplaces for industrial production, ensuring robust, scalable, and interoperable systems across diverse manufacturing environments.

5.3 Evaluation of the industrial metaverse architecture

This section discusses the broad-reaching effects and future directions stemming from the study on the industrial metaverse architecture. This includes analysis on the varied contributions of our work and the challenges that arise in the evolving landscape of the industrial metaverse.

5.3.1 Merits of this work

This study on the industrial metaverse presents three interconnected contributions, each addressing distinct gaps in both the scholarly domain and industrial applications. Below, we detail these contributions and highlight their respective merits.

Novel architecture for industrial applications: Central to this study is the development of an innovative industrial metaverse architecture that connects physical factories with their digital counterparts. Unlike current models that focus on consumer use [79, 96, 34, 74] or offer only theoretical industrial frameworks [168, 73], this architecture is specifically tailored for smart factory applications, providing both theoretical insights and a practical blueprint for real-world implementations. Marked by scalability and interoperability, this architecture broadens the industrial metaverse scope to encompass a full range of components, including machines, personnel, materials, and the environment, building on previous digital twins and XR integration research [7, 2, 6, 163, 164] as well as in Publication I, and II.

Orchestrated data flow and knowledge synchronization: A key feature of our architecture is its orchestration of data flow and knowledge synchronization through digital twins and semantic models. This enables simultaneous updates in both physical and digital spaces, enhancing data utility. The architecture uses a T-box and A-box system, with the T-box for the ontological schema, providing a stable knowledge framework, and the A-box for live, operational data in digital twins, ensuring dynamic data representation. This dual structure ensures consistency and currentness in both physical and virtual spaces. Additionally, the architecture's integration with existing industry systems via semantic models facilitates interoperability and practical applicability without requiring extensive system modifications.

Validation through a case study: The validity of the proposed industrial metaverse architecture is demonstrated through a case study focused on tracking material flow within a plant. This practical test confirms the architecture's functionality, providing tangible evidence supporting our theoretical design. Unlike prior studies often fixated on XR technology alone [162, 73, 102, 3], the case study adopts a broader view, emphasizing the seamless integration of digital and physical spaces and underscoring often-overlooked elements like data integration and semantic modeling.

5.3.2 Challenges and future works

Despite these contributions to the industrial metaverse development, the work also recognizes certain constraints and suggests seven directions for future exploration as follows.

Comprehensive validation: While our case study serves as an initial proof-of-concept, further exploration into a wider array of scenarios and complexities is necessary to validate the robustness and adaptability of the architecture. Future research should focus on extensive validation across various industrial contexts to assess the architecture's effectiveness. It's crucial to measure the actual impact on industrial metrics such as manufacturing efficiency, error rates, and cost efficiency through quantitative analysis.

Customization and personalization: The modularity and scalability of the proposed architecture allow it to flexibly meet diverse industry-specific needs. Future research will focus on creating customized modules and functionalities that cater to the unique requirements of various sectors, involving consultations with industry experts to integrate best practices and standards effectively. Additionally, enhancements in personalization capabilities will enable adjustments to individual or organizational preferences, significantly boosting user engagement and operational efficiency. The adaptability of the architecture will be rigorously validated for its functionality and integration with both legacy systems and new technologies.

Multi-user interaction: While the current implementation of the XR interface primarily supports individual interactions, future enhancements will focus on expanding its capabilities to enable multi-user virtual collaboration. This is essential to fully realize the Industry 5.0 vision of collaborative industrial environments where interdisciplinary teams and customers can interact not only physically but also through a virtual space. Enhancing the XR Interface to support avatars and shared virtual experiences will allow for activities such as joint training sessions and collective operations. Additionally, future development should include a more detailed representation of personnel digital twins and personnel profiles to manage digital identities and facilitate active multi-user participation in the metaverse.

Real-world data challenges: The foundational data management capabilities of the proposed architecture are tested in a controlled lab in this work, yet real-world factory settings introduce challenges like data integrity, rapid communication, and robust cybersecurity. The employment of the 5G network in the case study is vital for high-speed data transmission and low latency, crucial for the industrial metaverse. Despite 5G's potential, actual speeds can vary, making empirical verification of data speeds and system latency essential. Future research must ensure the network's effectiveness and cybersecurity across various settings to address these practical challenges effectively and maintain the architecture's robustness in complex industrial environments.

Human factors and human-centric design: The proposed architecture leverages XR for HMI, which requires thorough investigation into its ergonomic and psychological effects. XR interface design must focus on usability, accessibility, and adaptability, upholding human-centric principles that enhance ergonomic comfort and psychological well-being. Given the importance of operator autonomy in Industry 5.0, which varies with cultural and educational backgrounds, it is essential to develop interfaces that adapt to diverse user needs, ensuring inclusivity and effective integration of human and machine efforts in digital workspaces.

Environmental impact: The industrial metaverse's sustainable deployment is challenged by the resource demands of data centers and XR devices. Future initiatives will enhance energy efficiency and adopt sustainability practices, such as utilizing advanced virtualization to reduce hardware needs and improving server efficiency. Energy-efficient hardware and algorithms will also reduce power usage. Additionally, incorporating renewable energy sources and innovative cooling techniques will minimize energy consumption. Sustainable manufacturing practices, promoting recyclability, and supporting a circular economy will address the lifecycle impacts of hardware.

Ethical and regulatory considerations: The swift development of industrial metaverse technologies, especially the use of digital twins for personnel, may lead to ethical and regulatory challenges concerning privacy, consent, and surveillance. The need for rigorous privacy measures and transparency is paramount when handling sensitive data from health records, employee monitoring systems, or wearable devices. Concerns are heightened with blockchain's role in enhancing transaction security but potentially compromising privacy. Future work must establish policies and standards that secure personal data, ensure transparency, and revise regulatory frameworks to keep pace with technological advances. This is vital for protecting individual well-being and balancing innovation with human dignity.

5.4 Overall scientific and practical implications of the thesis

This thesis advances the integration of digital twins and XR, establishing a comprehensive architecture for the industrial metaverse, and paving the way towards Industry 5.0. It covers the development and assessment of an MR application for crane operations, the formulation of the TwinXR method for synergizing digital twins and XR, and the design of an industrial metaverse for smart factory applications. These initiatives demonstrate the transformative capacity of such technologies in revolutionizing industrial processes by enhancing data sharing, customization, and user engagement.

Scientifically, this work contributes to the field by synthesizing the advancements in XR, digital twins, and industrial metaverse. The work first develops a novel MR interface for operating a digital twin-based industrial crane system, and defines a measurement protocol to assess its control accuracy. The TwinXR method, with its emphasis on scalability and adaptability, offers a novel approach to integrating digital twins with XR, broadening the scope of application across various industrial scenarios. Moreover, the proposed industrial metaverse architecture introduces a novel paradigm for merging physical factories and the virtual landscape, facilitating seamless data flow and knowledge synchronization leveraging digital twins and semantic models.

From a practical perspective, the thesis provides actionable solutions and frameworks for deploying XR, digital twins, and metaverse technologies in industrial operations. These innovations align with Industry 5.0's goals of smarter, more resilient, and human-centric industrial environments. The practical application of these technologies can significantly impact manufacturing efficiency, error reduction, cost management, and overall operational agility.

In summary, this thesis not only contributes to academic discourse but also serves as a blueprint for industrial practitioners looking to leverage XR, digital twins, and metaverse technologies in pursuit of Industry 5.0 goals. It advocates for a collaborative approach among researchers, industry stakeholders, and policymakers to navigate the complexities of integrating these advanced technologies into practical industrial applications, ultimately aiming to create more resilient, sustainable, and human-centered industrial systems.

6. Conclusion

This dissertation marks a significant journey, bridging the gap between the automation and data exchange ethos of Industry 4.0 and the collaborative, human-centric vision of Industry 5.0 through the industrial metaverse. At the heart of this transition is the seamless integration of digital twins and XR technologies, reshaping the landscape of industrial operations and fostering a new era of human-machine symbiosis.

The MR interface for digital twin-based crane, as the initial step in this research journey, demonstrates the feasibility and effectiveness of employing MR for complex industrial machinery control and monitoring, laying the groundwork for further explorations into the integration of digital twins and XR. Following this, the TwinXR method is introduced, showcasing the robustness and scalability of using digital twin descriptions across various industrial XR applications. The culmination of this research in proposing a comprehensive industrial metaverse architecture, exemplified through the in-plant material flow tracking case study, illustrates a practical approach towards achieving a resilient, interconnected, and scalable industrial metaverse. The findings from this research underscore the transformative potential of digital twins and XR as key drivers in revolutionizing industrial processes. By augmenting human capabilities and driving the digital transformation imperative, this work contributes significantly to the narrative of Industry 5.0, encapsulating a synergy of digital and physical interactions, enhanced operational efficiency, and a collaborative industrial ecosystem.

Looking ahead, the thesis outlines crucial future research directions for the further development and widespread adoption of these technologies within the Industry 5.0 paradigm. This includes conducting extensive validation in diverse industrial scenarios, tailoring solutions to meet specific industry requirements, addressing challenges related to real-world data integration, focusing on sustainability and ethical considerations, and emphasizing human factors in technology design.

This research journey, while charting a path from Industry 4.0 to Industry 5.0 through the industrial metaverse, represents a paradigm shift in industrial operations. The integration of digital twins, XR, and the metaverse stands as a beacon for future innovations in smart manufacturing, promising a future where technology and human ingenuity coalesce to create a more efficient, sustainable, and collaborative industrial world.

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Aalto-DT 171/2024

ISBN 978-952-64-1978-7 (printed)
ISBN 978-952-64-1979-4 (pdf)
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)

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