Tampere University

TERO KAARLELA

A Common Digital Twin Platform for Education, Training and Collaboration

Tampere University Dissertations 814

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ACADEMIC DISSERTATION
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of Tampere University,
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ABSTRACT

The world is in transition driven by digitalization; industrial companies and educational institutions are adopting Industry 4.0 and Education 4.0 technologies enabled by digitalization. Furthermore, digitalization and the availability of smart devices and virtual environments have evolved to produce a generation of digital natives. These digital natives whose smart devices have surrounded them since birth have developed a new way to process information; instead of reading literature and writing essays, the digital native generation uses search engines, discussion forums, and online video content to study and learn. The evolved learning process of the digital native generation challenges the educational and industrial sectors to create natural training, learning, and collaboration environments for digital natives.
Digitalization provides the tools to overcome the aforementioned challenge; extended reality and digital twins enable high-level user interfaces that are natural for the digital natives and their interaction with physical devices. Simulated training and education environments enable a risk-free way of training safety aspects, programming, and controlling robots. To create a more realistic training environment, digital twins enable interfacing virtual and physical robots to train and learn on real devices utilizing the virtual environment. This thesis proposes a common digital twin platform for education, training, and collaboration. The proposed solution enables the teleoperation of physical robots from distant locations, enabling location and time-independent training and collaboration in robotics.

In addition to teleoperation, the proposed platform supports social communication, video streaming, and resource sharing for efficient collaboration and education. The proposed solution enables research collaboration in robotics by allowing collaborators to utilize each other's equipment independent of the distance between the physical locations. Sharing of resources saves time and travel costs. Social communication provides the possibility to exchange ideas and discuss research. The students and trainees can utilize the platform to learn new skills in robotic programming, controlling, and safety aspects.

Cybersecurity is considered from the planning phase to the implementation phase. Only cybersecure methods, protocols, services, and components are used to implement the presented platform. Securing the low-level communication layer of the digital twins is essential to secure the safe teleoperation of the robots. Cybersecurity is the key enabler of the proposed platform, and after implementation, periodic vulnerability scans and updates enable maintaining cybersecurity. This thesis discusses solutions and methods for cyber securing an online digital twin platform.

In conclusion, the thesis presents a common digital twin platform for education, training, and collaboration. The presented solution is cybersecure and accessible using mobile devices. The proposed platform, digital twin, and extended reality user interfaces contribute to the transitions to Education 4.0 and Industry 4.0.

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ABBREVIATIONS

AI	Artificial Intelligence
AMQP	Advanced Message Queuing Protocol
API	Application Programming Interface
AR	Augmented Reality
Blender	An open-source 3D computer graphics software tool set
C++	A high-level, general-purpose programming language
C#	A general-purpose, high-level multi-paradigm programming language
CA	Certificate Authority
CMS	A Content Management System
CNC	Computer Numerical Control
CPS	Cyber-Physical System
DIH	Digital Innovation Hub
DT	Digital Twin
FK	Forward Kinematics
HRC	Human-Robot Collaboration
HTML5	A markup language used for structuring and presenting content on the World Wide Web
IDS	Intrusion Detection System
IIoT	Industrial Internet of Things
IK	Inverse Kinematics
IPS	Intrusion Prevention System
IT	Information technology
JavaScript	A high-level, often just-in-time compiled language

JSON	An open standard file format and data interchange format
MQTT	Message Queue Telemetry Transport protocol
NIST	National Institute of Standards and Technology
Node-RED	A flow-based development tool for visual programming
OPCUA	Open Platform Communications Unified Architecture
OT	Operational technology
PLM	Product Lifecycle Management
PTP	Point To Point
Python	A high-level, general-purpose programming language
RGB-D	A depth and color sensing camera
RoboDK	An offline programming and simulation software for industrial robots
SME	Small and Medium-sized Enterprise
TCP	Tool Center Point
TCP/IP	Transmission Control Protocol / Internet Protocol
UADP	Unified Architecture Datagram Protocol
Unity3D	A cross-platform game engine
Unreal Engine	A cross-platform game engine
URP	Universal Render Pipeline
VC	Virtual Commissioning
VE	Virtual Environment
WebAssembly	A portable binary-code format and a corresponding text format for executable programs
WebGL	A JavaScript API for rendering interactive 2D and 3D graphics with web browser
WebXR	WebXR device API enables a platform-independent XR-experience
XR	Extended Reality

ORIGINAL PUBLICATIONS

Publication I T. Kaarlela, S. Pieskä, and T. Pitkäaho. “Digital twin and virtual reality for safety training”. In: *11th IEEE International Conference on Cognitive Infocommunications, CogInfoCom 2020 - Proceedings* (2020). doi: 10.1109/CogInfoCom50765.2020.9237812.

Publication II Tero Kaarlela et al. “Robot cell digital twins as a tool for remote collaboration between organizations”. In: *2022 IEEE/SICE International Symposium on System Integration (SII)* (2022). doi: 10.1109/SII52469.2022.9708902.

Publication III Halldor Arnarson et al. “Evaluation of cyber security in agile manufacturing: Maturity of Technologies and Applications”. In: *2022 IEEE/SICE International Symposium on System Integration (SII)* (2022). doi: 10.1109/SII52469.2022.9708888.

Publication IV T. Kaarlela et al. “Common Educational Teleoperation Platform for Robotics Utilizing Digital Twins”. In: *Machines* (2022). doi: 10.3390/machines10070577. url: https://www.mdpi.com/2075-1702/10/7/577.

Publication V Tero Kaarlela et al. “Digital Twins Utilizing XR-Technology as Robotic Training Tools”. In: *Machines* (2022). doi: 10.3390/machines11010013. url: https://www.mdpi.com/2075-1702/11/1/13.

Author’s contribution

Publication I The author designed the study and was responsible for practically implementing the first two studies. The author was also responsible for the literature review with Sakari Pieskä. The publication was written by the author with the help of Sakari Pieskä and Tomi Pitkäaho.

Publication II The author designed educational studies and was responsible for implementing studies B and C. The author was also responsible for the literature review with Sakari Pieskä and Beibei Shu. The author wrote the publication with the help of other authors.

Publication III The author was responsible for writing the introduction, state-of-the-art, cybersecurity in manufacturing, and conclusion sections together with the other authors.

Publication IV The author was responsible for defining the methodology for this work with Tomi Pitkäaho. The author designed three of the studies and was responsible for the practical implementation of those studies. The author was mainly responsible for the software development with Beibei Shu and Halldor Arnarson. Requirement specification and design specification were defined by the author and Tomi Pitkäaho.

Publication V The author was responsible for conceptualizing this work with the other authors. The methodology was defined by the author and Tomi Pitkäaho. The author was responsible for the software development with Paulo Padrao. The author defined requirement specification and design specification. The author was also responsible for the administration of the writing process.

1 INTRODUCTION

Education, training, and collaboration are fundamental cornerstones of modern civilization. Collaboration enables greater intelligence, faster problem solving, and innovation capabilities than a single individual can achieve [53, 33]. Education and training are closely related; the main difference is the aim. Education aims to increase the level of knowledge, while training aims to practice a new skill [112]. In the past, individuals have traveled to on-site events to collaborate, gain knowledge and practice new skills. Teaching, training, and collaboration have consisted of on-site activities such as; participating in lectures, group work, and laboratory exercises. Reading books to gain knowledge and writing an essay to present and prove the gained knowledge is an example of a typical assignment [94].

Digitalization has evolved to produce a new generation of digital natives, who have grown up with digital devices and learn by utilizing web searches, social platforms, internet forums, and Virtual Environments (VEs) [98, 59]. Trainers and educators of today are challenged to create natural training, learning, and collaboration environments for the digital native generation [23, 13]. While digitalization has created the aforementioned challenge, digitalization also provides new tools for education, training, and collaboration. VEs are replacing class and meeting rooms, freeing participants from physical constraints. The ongoing digital evolvement in education is referred to as Education 4.0 to reflect the fourth generation of education [72].

A parallel evolvement of digitalization in the industry is referred to as Industry 4.0, reflecting the adaptation of similar possibilities [58, 38]. Utilization of advanced technologies such as Virtual Engineering, Industrial Internet of things (IIoT), Artificial Intelligence (AI), Virtual Commissioning (VC), Digital Twin (DT), cloud computing, and Extended Reality (XR) can increase the efficiency of manufacturing and education [77, 40].

VEs based on high-level XR user interfaces provide a learning environment natural to the digital-native generation and an effective training and collaboration environment for industrial applications. VEs enable training and education scenarios that are difficult to implement in traditional classrooms, limited by the physical constraints of the real world. XR enables risk-free training for the safety aspects and operation of production equipment. Virtual training environments for hazardous situations and complicated industrial assembly processes are easy to reset and replay. XR enables immersive training utilizing virtual reality (VR) and training environments augmented with virtual elements. Augmented reality (AR) and augmented virtuality (AV) can enrich virtual and real environments by integrating virtual elements into the real world or integrating real elements into the virtual world.

VEs presented in this thesis are WebXR-based, providing an accessible cross-platform user interface. The platform provides tools for sharing the time resource of the equipment, video streaming, social communication, and teleoperation of the connected robots. A fully virtual training does not enable a realistic experience for the trainee or an engineering student [96]. Furthermore, the VE does not enable sharing of hardware between the collaborators. Digital Twins (DTs) enable interaction with real hardware to provide a realistic virtual experience and access to physical robots for the trainee, student, and collaborator.

Bidirectional communication connects the real and virtual worlds, enabling the teleoperation of the physical robot from the VE. Furthermore, DTs validate robot trajectories before execution on real hardware to provide a safe environment for exercising and piloting. As the industry is transitioning to the metaverse, the DTs are core components of the transition [105]. DTs enable interfacing the physical production equipment with the virtual entities, merging virtual and real worlds [78]. The metaverse enables multi-user VEs for working, training, socializing, and engineering [91].

This thesis presents a prototype of a common DT platform. This platform enables a novel and cybersecure way to utilize DTs for training, teaching, and collaboration in robotics, utilizing VEs suitable for Industry 4.0 and Education 4.0.

1.1 Objectives and scope

This thesis aims to develop a prototype of a common DT platform for robotic education, training, and collaboration. The platform prototype enables social communication, video streaming, resource sharing, and remote robotics training utilizing teleoperation. The research problem of this thesis is the following:

There is a barrier preventing physical access to the laboratory, so an alternative access method is required.

The barrier preventing access to robots in the scope of this thesis is the physical distance between the operator and the robot. The evolvement of the digital native generation, environmental awareness, and pandemic restrictions shape the way of learning, training, and collaboration. Virtual access to the production environment or the educational laboratory enables the utilization of robots without traveling to the site, saving time and environmental resources. Furthermore, virtual environments enable risk-free and productive training in robotics. The resource-sharing feature of the platform enables an effective sharing of the connected robots, resulting in a higher equipment utilization rate.

The proposed platform's system architecture enables a broad selection of DTs in the educational and industrial domains; however, this thesis focuses on DTs in the robotics domain. Cybersecurity (CS) is in the scope of this thesis and is considered during the implementation of the platform and the literature review.

1.2 Research questions and contributions of the publications

Research questions are based on the research problem and the objectives presented. To solve the research problem, the following three research questions are investigated:

- **RQ1:** In what manner teleoperation platform utilizing DTs is technically feasible for robotics education and training?
- **RQ2:** What are the benefits and challenges of utilizing XR technologies for robotics training?
- **RQ3:** What are the main CS challenges that might hinder the use of teleoperation in robotics?

The relationships between research questions, methods utilized, and dissertation publications are presented in Figure 1.1. The roman numerals refer to the contributing publications.

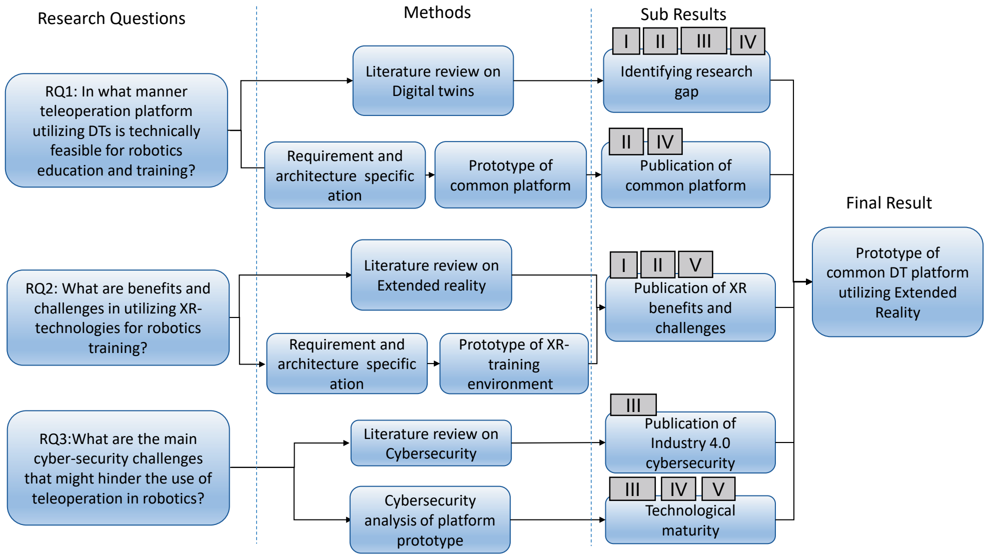

Figure 1.1 The thesis research questions and contributions of the publications to the research questions.

1.3 Scientific contributions

This thesis contributes to new practical and scientific knowledge of DT implementations for Industry 4.0 and Education 4.0, bridging the interaction gap between industry and academia by introducing a common platform for collaboration. Knowledge is gained by developing a prototype of a common DT platform utilizing XR technologies, evaluating user feedback, and assessing cybersecurity.

The first contribution is the prototype of a novel common DT platform for education, training, and collaboration. The prototype was conceptualized in publications I and II after a literature review and development of an initial prototype. Publication IV defined requirements and architecture for an evolutionary prototype of the common platform. More advanced DTs and high-level XR user interfaces for the platform prototype were developed in publication V. Prototype of a robust online platform presented is a key enabler for virtual learning factories and online pedagogical experiments. The final prototype answers research question 1.

The second contribution of this thesis is the methods to evaluate the benefits and challenges of utilizing XR technologies for robotics training. The methods to validate the platform are presented in publications IV and V, and the authors of the publications conducted initial functionality validations. A group of volunteer students piloted the proposed platform to enable the collection of comprehensive feedback on the benefits and challenges. The feedback results are evaluated, presented, and discussed in this thesis. The presented guidelines can be used to evaluate the benefits and challenges of XR technologies in future training applications. The evaluation provided answers to research question 2.

The third contribution of this thesis is the methods to assess and evaluate the cybersecurity of an online common DT platform. The findings in publication II and the cybersecurity evaluations conducted in publication III contributed to the cybersecure design of the presented platform prototype. Cybersecurity Requirements were considered during the common platform prototype's requirements, architecture specifications, and implementation in publications IV and V. The methods presented are not limited to the online DT platform presented. Instead, methods can be used to assess and evaluate various DT platforms. The cybersecurity assessment answers research question 3.

1.4 Research ethics

The research work for this thesis follows guidelines for good scientific practice published by the Finnish Advisory Board of Research Integrity[97]. Honesty, care, and accuracy have been followed during the research work and reporting of the results. The work of other researchers has been respected by adding appropriate references to the original publications. All the images and figures in the publications and this thesis are provided or drawn by the authors to avoid copyright issues. Furthermore, all text is written by the authors of the publications, and none of the text has been published earlier [97, 101]. Consent from volunteers was obtained during data collection and piloting the proposed platform in publication IV. To guarantee the anonymity of the participants, personal details were not collected.

1.5 Outline of the thesis

Chapter 1 presents the motivation and ethics guidelines for the thesis, the scope, and the research questions. Chapter 2 introduces the concept of DT and reviews the history of XR and state-of-the-art XR training platforms. Chapter 3 presents the methods to prototype the common DT platform for education, training, and collaboration. The fourth chapter presents the case studies of the dissertation. Chapter 5 presents the thesis results, a common DT platform prototype, architecture, DTs, and communication layer. Chapter 6 discusses the key findings of this thesis, and Chapter 7 concludes the dissertation.

2 LITERATURE REVIEW

The first section of this chapter presents the concept of Digital twins. And the following section presents a brief history of extended reality (XR) and state-of-the-art XR training platforms for robotics, aiming to identify the research gap of this thesis. The focus is on training platforms enabling the programming and control of the robots. The review articles were selected using IEEEXplore, ScienceDirect, and MDPI search tools targeting "virtual training platform" and "digital twin platform" in the title, abstract, and keywords. The search was chronologically restricted between 2015 and 2022. The aim of the last section of this chapter is to review communication protocols to choose an efficient protocol for designing and implementing the communication layer for the presented platform.

2.1 The digital twin concept

This section describes the concept of DTs presented by Grieves in 2003 during his course on product lifecycle management (PLM). Grieves defined DT as *a set of virtual information constructs that fully describes a potential or actual physical manufactured product* [34]. The concept was presented as a conceptual ideal for PLM, consisting of three components linked together from the design phase to the disposal phase: physical twin, DT, and data connection between the twins [34]. The near real-time data connection between the twins enables visual conceptualization, comparison, and collaboration on a physical system, utilizing the DT [33]. In 2010, NASA Modeling, Simulation, Information Technology, and Processing Roadmap defined DT as a digital counterpart of a physical air vehicle [104]. Since the presentation of the concept by Grieves, the definition of DT has been evolving, and multiple definitions and even misinterpretations of the concept have existed [31, 81].

Grieves divides DTs into DT Prototypes (DTP) and DT Instances (DTI) [33]. A DTP is a digital presentation containing all the information necessary to produce a prototypical physical twin. A DTI is a more advanced digital copy of the actual system linked together throughout the complete lifecycle of the physical twin. Kritzinger [55] categorizes DTs, according to the three levels of data integration: digital model, digital shadow, and DT. The three levels are presented in Figure 2.1. A digital model is a digital presentation of the physical object, and no automated data flow between the two exists, a digital shadow is a digital presentation of the physical object with uni-directional automated data flow from physical to digital object, and DT is a digital presentation of the physical object featuring automated bidirectional data flow [55]. According to Cimino, DTs are virtual copies of systems able to interact in a bidirectional way [14].

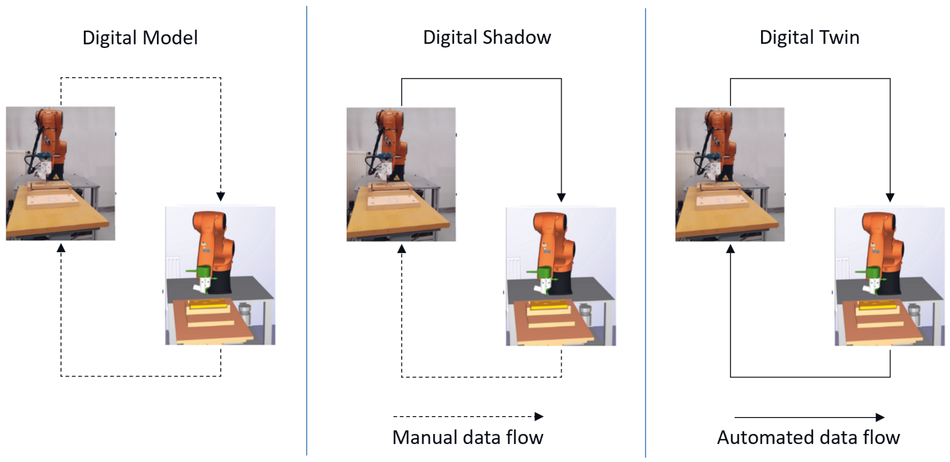

Figure 2.1 Three integration levels: digital model, digital shadow and digital twin [55]

The DT Consortium provides the following solid definition for DTs: A DT is a virtual representation of real-world entities and processes synchronized at a specified frequency and fidelity [22]. Despite the minor deviations in the definitions, the three main elements of the original conceptual ideal presented by Grieves remain: physical twin, DT, and data flow between the two. The International Organization for Standardization has defined standards for the DT framework [46]. A standardized framework reflects the DT as a mature concept for industrial applications.

The DT, as a digital counterpart of the physical system, presents parameters such as temperature, velocity, pressure, and frequency of the physical twin as a digital presentation. In addition to a digital model and data connection to the physical twin, the digital part contains a structure and algorithms to mirror the physical constraints and the functionalities of the physical counterpart [100]. The DT enables the user to utilize low-level functions enabled on the physical twin. DTs enable analyzing and optimizing physical systems and processes manually or using artificial intelligence. DT consortium provides a glossary of the terms related to DTs. The following terms are referenced later on [22]:

- DT is a virtual presentation of real-world entities and processes synchronized at specified frequency and fidelity.
- Physical twin is a set of real-world entities and processes that correspond to a DT.
- DT platform is a set of integrated services, applications, and other DT subsystems that are designed to be used to implement DT systems.

DTs can be utilized to twin a single physical system, such as a machining center, a construction machine, or an autonomous vehicle [4], or larger entities, such as digital factories, smart cities, supply chains, and energy systems [30, 65, 87].

An example of a DT platform for education, research, and innovation is an overhead crane *Ilmatar* [8]. *Ilmatar* is a smart crane specially equipped by the manufacturer. IoT sensors and actuators enable access to the crane's low-level control and sensor data utilizing an OPC UA server. The *Ilmatar* has been utilized as a DT platform in doctoral and masters student projects for automated, high-accuracy lifting, mixed reality (MR) remote control, and XR application framework for the overhead crane DT [117, 3, 113]. In addition to student projects, *Ilmatar* has fueled doctoral theses for API-based DT architecture and DT Web [7, 2], merging industrial and educational research.

In the context of this thesis, a common DT platform for the education, training, and collaboration of robotics is proposed. The platform enables social communication, resource sharing, and teleoperation of robots, providing a foundation for studying, training, and researching robotics. DTs are the tools that enable the user to interact with physical robots and their digital counterparts utilizing a VE. Furthermore, the DTs validate the trajectories created by the user to confirm the execution of only safe moves inside the reach area of the robot.

2.2 Extended reality robotic training platforms

XR has been studied for decades; pioneers in the field have researched virtual reality [35], augmented reality [108], and augmented virtuality [56].

The devices enabling immersive and augmented XR experiences result from development work in the fields of entertainment [36], optics [41], electronics [50], and computing. Mobile phones and tablets are affordable devices to experience XR. Mobile devices enable native AR support and immersive VR experiences utilizing a VR headset casing. Milgram presented the reality-virtuality continuum to define XR as the main category for VR, AR, AV, and the subcategory of MR to categorize AR and AV [71]. Figure 2.2 presents XR and related subcategories.

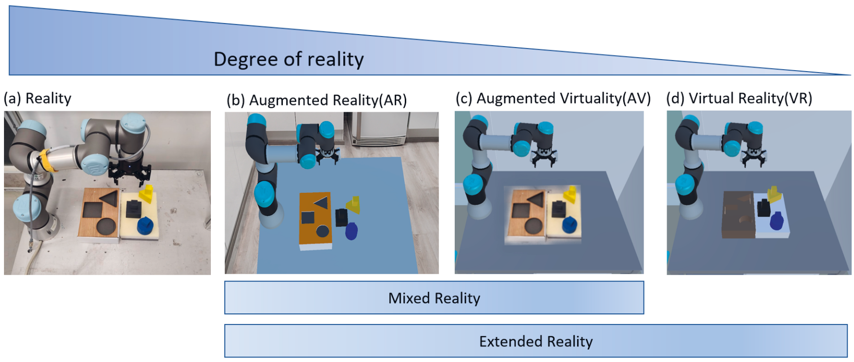

Figure 2.2 Reality-virtuality continuum. (a) reality, (b) AV, (c) AR, and (d) VR. (Publication V)

Crespo et al. [17] developed an offline training environment for an industrial robot, utilizing the Unity3D game engine. The proposed immersive VR environment evaluates the trajectories defined by the user and calculates the shortest collision-free path to the target before executing the trajectory on the physical robot. The proposed solution can also compare and evaluate the autogenerated trajectory to the one created manually by the user. Based on the feedback of twenty engineering students piloting the developed training environment and the total times measured to complete the exercises, robot programming utilizing XR is more effective than programming using the teach pendant.

Perez et al. [92] proposed an immersive solution enabling the training of robot control and programming in VR. The publication mentions a connection to the physical robot in the laboratory; however, the implementation details of the connection, such as communication protocol, are not provided. According to the feedback, the time required for robot operator training was reduced, and the proposed VR solution was user-friendly. An AR application to enable training in robotics utilizing the touchscreen of a mobile device was proposed by Bogosian et al. [11]. The proposed solution was piloted by construction workers training in basic control of an industrial robot.

Dianatfar et al. [21] proposed an XR safety training concept for human-robot collaboration. The system consisted of the trainee, a VR headset, and a workstation PC. The standard ISO 10218-2, describing safety requirements for industrial robots, and technical specification ISO/TS 15066, providing regulations for collaborative robots, are the guidelines for implementing the proposed concept. The proposed safety training environment enables visualizing the shared workspace and the assembly sequence. Also, as a unique feature of the proposed solution, the trainee can hand-guide the robot in specific assembly processes and predict the robot's next movements.

Monetti et al. [73] developed a prototype of a VR training environment to compare the efficiency of manual robot programming and VR application. The VR environment enables the user to create trajectories for the robot by drawing in the air and closing the gripper by pinching. Furthermore, active guidance and collision avoidance functions assist in trajectory generation. Three tasks were defined for the pilot group to validate and pilot the prototype. The participants utilizing the proposed VR solution conducted robot programming faster than the ones utilizing a teach pendant, with a higher pass rate. These results Prove that VR is an efficient and easy way to program robots. [73]

Garg et al. [29] proposed a DT framework to create and validate robot trajectories, enabling the safe teleoperation of robots. BioIK asset of Unity3D enabled inverse kinematics (IK) calculation for the virtual robot. The communication layer of the proposed solution utilizes a socket messaging protocol to access robot variables and parameters. The VR environment enables the user to create and validate trajectories and target points by pointing and clicking features of the three-dimensional elements. The authors mention dependency on the Fanuc robot controllers as a system's weakness. The measured accuracy of the system on the physical robot joints was between 0.3 and -0.3 degrees, and the communication latency was approximately 40 milliseconds.

Rofatulhaq et al. [99] developed a virtual engineering platform for engineering students during the COVID-19 pandemic. The proposed platform consists of a WebXR application, data storage, a communication layer, and physical laboratory equipment. The proposed platform has a unique feature to form and store a three-dimensional avatar of the user utilizing a depth camera. The communication layer, implemented with Message Queue Telemetry Transport (MQTT) protocol, enables the user to teleoperate the industrial robot on the platform utilizing a digital model in VR. Five simultaneous users tested the latency of the MQTT protocol. The measured latency of the messaging is about 44 milliseconds, enabling 22 messages per second.

In addition to data from the robots, it is possible to augment data of the surrounding environment to DT. Xin et al. [60, 61] proposed a multisource model-driven DT system to enable the user to visualize the surrounding environment in addition to the teleoperated robot. The surrounding sensing system consists of an RGB-D camera and a force sensor attached to the robot flange to visualize an object's position, pose, and color in VR. In addition, the framework enables visualization of the object's deformation caused by the gripper's linear force. Preset data of the object's density and force sensors on the robot flange and gripper enable an algorithm to calculate object deformation, enabling realistic rendering of manipulated objects in the VE.

Erdei et al. [25] proposed a digital training center for robots. The robotics laboratory was virtualized to overcome pandemic restrictions and the limitations of a physically small laboratory. The proposed solution enables importing three-dimensional models into VE and controlling the virtual robot by jogging. The user can program the robot utilizing linear, circular, and PTP movements and gripper commands. Saving and running the recorded programs is enabled to verify programs. Two groups piloted the proposed solution; it was observed that the group that was provided the opportunity to train on VE before exercising on the physical robot experienced significantly shorter times to program the physical robot. [25] Although the DT is mentioned in the topic of this article, there is no DT implemented, only a virtual copy of the robotics laboratory.

Mourtzis et al. [74] presented a teleoperation framework utilizing AR. The framework consists of two modules; the navigation module and the animation module. The navigation module provides visual feedback on the maximum reach point of the robot. Color codes from close to the robot base to the unreachable area are; green, yellow, orange, and red. The animation module enables similar functionality of the collision distance between the robot arm and the objects. The proposed solution utilizes Robot Operating System (ROS) as a middleware for IK and forward kinematics (FK) [74]. A group of five volunteers piloted the proposed framework by conducting assembly and pick-and-place tasks. The visual feedback decreased the total completion time of the assembly task by 24%, and the number of user errors decreased by 60%.

In conclusion, multiple approaches to virtual robotic training platforms have been proposed. In most cases, virtual models were assembled and textured utilizing Blender, and Unity3D was used to compile the VE. In one of the presented cases, the Unreal Engine was utilized as a game engine instead of Unity3D. Most of the proposed solutions concentrate on supporting only VR technology. VR as an immersive technology requires using specific devices such as VR headsets and handheld controllers. Only two reviewed proposals utilized AR technology and support for mobile devices utilizing WebXR.

WebXR enables distributing XR applications on the web by utilizing a combination of HTML5 [39], WebGL [51], WebXR, and WebAssembly [110]. WebXR applications are cross-platform, accessible, and cybersecure. Only one of the publications utilized AV to augment real elements in the VE. A few of the proposed platforms support the teleoperation of the physical robot utilizing a DT. None of the reviewed publications support resource sharing or social communication. Cybersecurity is not a major concern of the authors in any of the reviewed publications, indicating the need for CS evaluation. A summary of the review findings is presented in Table 2.1

2.3 The communication layer

The communication layer between the digital and physical twins is a key enabler of the DT concept [32]. An effective communication protocol is required to exchange data at a specified frequency and fidelity. In the early days of industrial automation, Operational Technology (OT) and Information Technology (IT) were isolated and did not share common standards [77]. OT and IT have become interconnected during the last two decades [12]; OT has adopted common IT communication standards such as Ethernet and TCP/IP for data exchange.

While adapting IT communication standards to enable OT connectivity, it is at the expense of exposing production systems to CS attacks [115, 52, 18]. The most common communication protocols and methods utilized in industrial applications are presented in the following sections. CS considerations are provided in section 3.4. Microsoft was one of the pioneers of merging OT and IT, introducing OPC (OLE for Process Control) as a part of the server product suite BackOffice in 1996 [10]. Microsoft introduced OPC as a solution for manufacturing companies to utilize production data in Office products. The client-server architecture-based OPC was widely accepted by equipment manufacturers and utilized in equipment ranging from industrial to embroidery machines. However, OPC was tied to the

Microsoft Windows operating system, limiting utilization for production equipment manufacturers and industrial companies not using the Windows operating system [27].

OPC Unified Architecture (OPC UA) was introduced ten years later as a successor to the OPC, enabling a cross-platform open standard IEC62541 for data exchange[26]. In addition to Microsoft, OPC UA is developed by an independent committee OPC Foundation[26]. OPC UA is an Industry 4.0 reference standard utilized widely in industrial automation[24, 76]. OPC UA standard amendment 14 adds definitions for publisher-subscriber messaging protocols, enabling support for IIoT communication protocols such as MQTT, AMQP, and UADP, interfacing OPC UA with publisher-subscriber communications [26]. The OPC UA standard is widely utilized by industrial automation and robot manufacturers [1, 15, 88, 111].

MQTT protocol, developed by Andy Standford-Clark and Arlen Nipper [43], is a popular messaging protocol for IoT and IIoT [5]. MQTT is utilized in automotive, industrial, logistics, and smart home applications [75]. MQTT messaging architecture consists of a publisher, a subscriber, and a broker. A publisher is a device that publishes information such as the position and pose of robot joints to the broker using a certain topic. A subscriber is a device subscribing to published topics to receive information from the publisher. The broker exchanges the information between the publishers and subscribers of the topics. MQTT is a cybersecure protocol; both username-password authentication and encryption using Transport Layer Security (TLS) have been enabled since MQTT standard version 3.1.1. Authentication, authorization, and encryption are the CS methods for implementing the platform presented in this thesis. [89]

The OPC UA was selected as a local communication protocol since robot manufacturers widely support it. However, because OPC UA is not an efficient protocol for near real-time communications over the internet and exposing the robot controller OPC UA server to the outside of the laboratory network is not a cybersecure option, MQTT was chosen as a communication protocol for data transmissions external to the laboratory. MQTT enables efficient, cybersecure, and lightweight communication over the internet. In addition, robot manufacturers have adopted MQTT into standard communication protocols [1, 15, 111].

2.4 Research gap

While DTs have been applied to many use cases, no common DT platform is suitable for collaboration, education, and training. The XR robotic training platform implementations reviewed are fragmented and missing one or more of the following features: CS, social communication, video streaming, sharing of resources, teleoperation, support for mobile devices, or XR. Furthermore, AV was utilized in only one of the presented publications; CS, social communication, and resource sharing were missing from all reviewed publications. The platform proposed in this thesis enables these services, utilizes AV, and is cybersecure. Table 2.1 presents the missing features of the solutions reviewed in section 2.2.

Table 2.1 Summary of the review on virtual robotic training platforms

Publication	Year	VR	AR	AV	DT	Teleop.	Mobile
Crespo et al. [17]	2015	X	-	-	-	-	-
Perez et al. [92]	2019	X	-	-	-	-	-
Dianatfar et al. [21]	2020	X	-	-	-	-	-
Rofatulhaq et al. [99]	2020	X	-	-	-	X	X
Bogosian et al. [11]	2020	-	X	-	-	-	X
Garg et al. [29]	2021	X	-	-	X	X	-
Xin et al. [60]	2021	X	-	X	X	X	-
Monetti et al. [73]	2022	X	-	-	-	-	-
Erdei et al. [25]	2022	X	-	-	-	-	-
Mourtzis et al. [74]	2022	-	X	-	X	X	-

3 RESEARCH METHODS

This chapter presents the thesis's research approach and methods. This thesis follows the constructive [64, 49] research approach. The constructive approach aims to develop entities to provide solutions to practically relevant problems [64]. Since the research problem of the thesis is practically relevant, and the thesis aims to develop a prototype of the common DT platform, the constructive approach supports the development and evaluation of an implemented prototype as the final result. The constructive approach has been previously used by Sacks et al. [102, 103] to develop a framework for analyzing connections between the Building Information Model (BIM) and Lean, by Marinelli [67] to analyze connections between Human-Robot Collaboration (HRC) and lean manufacturing, and by Koho to assess and improve the production of mechanical engineering companies [54].

The main phases of the thesis are conceptualization, development, and validation. Publications I and II led to the conceptualization: *Common DT platform utilizing open communication standards is required for education, training, and collaboration of robotics*, and prototyping the initial prototype and architecture. The initial prototype was a throwaway prototype [20] intended to provide information for the later requirement specification.

In the development phase, the requirement specifications for the platform were defined, and an evolutionary prototype [20] was implemented to prove the concept. The final prototype of the platform presented in publication V is an evolution of the prototype presented in publication IV. The validation of the prototype consists of a cybersecurity assessment and a user survey. The methods to build, cyber secure, and validate the common platform, XR training environments, and DTs are presented in the following sections. Figure 3.1 provides an overview of the methods and relevant publications.

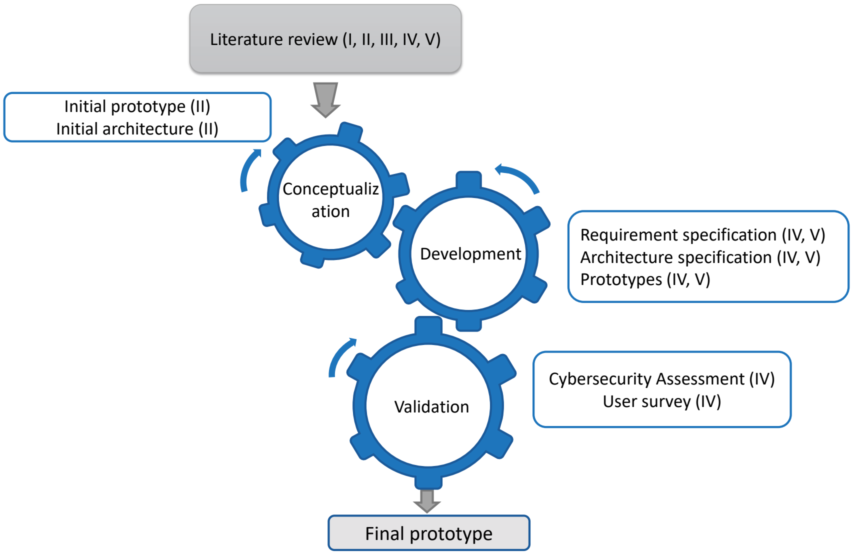

Figure 3.1 Methods utilized in this thesis; roman numerals indicate the relevant publications.

3.1 Prototype of the common digital twin platform

Two prototypes described in publications II and IV were developed to determine if a common DT platform is technically feasible for education, training, and collaboration in robotics. The key finding of publication II was essential for a common platform utilizing open communication standards. Industrial companies and educational institutions use various software products, and a common platform utilizing open communication standards enables collaboration regardless of different software products. Based on the knowledge gained prototyping DTs presented in publication II and the literature review in publications I and III, the system architecture and requirements specification for a common DT platform for education, training, and collaboration of robotics was defined in publication IV.
The requirement specification is considered an essential element of software development [116]. The requirement specification process followed IEEE Recommended Practice for Software Requirements Specifications [44]. Requirement specification aims to define functional and non-functional requirements for the evolutionary prototype of the platform. The functional requirements are defined to support answering the thesis's research questions and solving the research problem.

The non-functional requirements are related to quality and are divided into three subcategories: usability, security, and performance. The requirement specification is the fundamental guideline for architecture specification, development, and validation phases. The validity of the system is checked against the requirements specified. Cloud computing architecture was chosen to enable the on-demand availability of platform services to users. CS is considered by selecting only those components that enable a cybersecure platform in the planning phase.

The first-generation DTs for the prototype presented in publication IV are script-based. Physical limitations of the robots, such as joint limits and maximum working envelope, are defined as coded-in parameters in the DTs. In addition to physical parameters, DTs include programmed logic to check the validity of the requested trajectory against the defined physical parameters to prevent executing non-permitted trajectories of the robot.

3.2 Prototype of the extended reality training environments

Non-functional requirements were defined for virtual training environments to create guidelines for implementation. Scripting and evaluation criteria of the virtual training scenarios are copies of Centria's existing on-site training exercises for pick-and-place, assembly, and safety. A virtual model of the existing Robo3D Lab was obtained utilizing a laser scanner. Laser scanning produces a three-dimensional point cloud of the existing environment automatically and efficiently [48].

Unity3D was utilized to create the required functionality and compile the VEs [19]. Unity3D was chosen since it is cross-platform, supports WebGL [51], and provides MQTT connectivity [79]. Furthermore, the online asset store provides a variety of installable assets for Unity3D [47]. To enable the cross-platform optimized graphics, the universal rendering pipeline (URP) of Unity3D is utilized [109]. The WebXR Exporter asset allows the in-person player to interact with virtual objects.

Blender is utilized for prototyping virtual models for robotic training environments [57]. The kinematic models of robots are based on rigging and contain information on the physical parameters of the robot. ROS-industrial packages [69] are used to obtain three-dimensional models of robots. The inverse kinematics and rigging bind the virtual elements to assembly with constraints equal to the physical twin. In addition, colliders for stationary objects in the VE are defined to enable advanced collision avoidance.

3.3 Validation of the platform

High-level tasks were defined to validate the functionality of each robot station DT. The defined tasks enable validation of the functionalities required to perform the task utilizing the DT. If the user cannot perform the defined high-level task, the DT and the user interface require re-design and re-implementation to enable all the required functionalities for successfully completing the high-level task.

Piloting and user surveys collected comprehensive user feedback on the DT platform for robotics education and training. Piloting enabled volunteers to test and evaluate the common platform's social communication, resource sharing, video streaming, and teleoperation services. User feedback was collected after piloting by providing participants with a link to an online survey. The online survey method was chosen since it is easy to distribute to students, results are automatically summarized, and filling out the survey is easy [106]. The survey questions aimed to determine the benefits and challenges of XR for robotics training. In addition, comments were collected to brainstorm ideas for improving the platform further. The survey results are provided in section 5.2.

3.4 Assessing cybersecurity

CS was considered in the requirement specification phase of the developed platform prototype. The methods to cybersecure the platform are authentication, authorization, firewall ruling, data encryption, and vulnerability scans [86]. Authentication on the platform is based on the content management system (CMS). In addition to authentication, the front end enables users to register, create a strong password and recover a lost password. Authorization on the platform is also based on CMS and provides three types of user rights: authenticated user, content Editor, and administrator. Firewalls are set up to restrict access to the cloud and the local servers. Furthermore, the open authorization service on the platform enables the utilization of all services using a single username and password. Open authorization is a secure token-based standard for authentication and authorization [66, 80].

The firewall ruling restricts access to only ports required to utilize the platform's services [86]. In addition to port-based ruling, rules based on the user's geographical location restrict unwanted access to the platform services. Encryption secures the data transferred between the user workstation, cloud server, and laboratory environments [77]. The communication layer of the twins, video stream, social communication, and browsing of lecture materials on the platform are protected by data encryption. The vulnerability scanning reveals future CS issues on the platform. The methods to solve CS issues revealed by scanning are re-configuring and updating the vulnerable services.

4 SUMMARY OF CASE STUDIES

This section summarizes each of the dissertation publications. The following subsections provide the main results and key findings of the publications.

4.1 Publication I: Digital twin and virtual reality for safety training

The first publication evaluated the maturity level of VR for industrial safety training. The study consisted of three safety training use cases. The first use case was a VE of a highly automated production cell for building floor structures. The VE consisted of a gantry robot, floor structure, safety laser scanner, and tooling required to mill, nail, and glue the floor structure. The VE enabled immersive training of the manufacturing processes and the gantry robot's safety functions and areas. In the VE, trainees could safely trigger the robot's safety functions by crossing the visualized safety areas and observing the consequences. Furthermore, VE enables trainees to visualize and understand different stages of the manufacturing process in this HRC manufacturing cell. The use case described is a simulated model lacking connection with the physical environment.

The second use case consisted of three-dimensional models of the Centria Robo3D Lab, robot cells, and CNC machines. Digital twins (DT) of the robots were created utilizing RoboDK [45], and bidirectional communication was based on RoboDK drivers for the specific robot controllers. The purpose of this use case was to evaluate the benefits of implementing a DT for robotic training. The presented use case enabled the trainee to teleoperate and monitor robots utilizing the VE. In addition, Quuppa [90] intelligent location system was utilized to track the movements of the humans in the Robo3D Lab. The location system consisted of stationary beacons installed in the laboratory's ceiling and non-stationary tags integrated into the clothing of the humans. Spatial (x,y,z) positions provided a primitive method for the DT to locate and present the humans inside the virtual Robo3D Lab.

The third use case was a VE for underground emergency training. The purpose of the VE was to enable realistic training for mining workers in case of an emergency such as fire, explosion, or injury. Implementing training for emergencies in a mining environment would have been complicated. The virtual model for the underground training environment was based on point cloud data from a mining cave 400 meters below the ground. Training scenarios for fire, explosion, truck crash, and an injured co-worker were compiled using Unity3D. During the virtual training, the trainees would learn how to use a fire extinguisher and a first aid kit and report an emergency in the underground caves.

The main result of this publication was the literature review and the first DT implementation for the teleoperation of the robot. The key findings of this publication were: 1) VR enables an immersive way of training robotics, safety, and emergency procedures, and 2) DT enables a realistic training experience by bridging physical and virtual worlds.

4.2 Publication II: Robot cell digital twins as tools for remote collaboration between organizations

This publication aimed to evaluate DTs as tools for the collaboration of organizations. In the scope of this publication, collaborating organizations are Centria University of Applied Sciences and UiT, The Arctic University of Norway. Three use cases were evaluated utilizing DTs for collaboration in research and education. The first use case for research collaboration enabled sharing a robot station for welding. The second use case enabled a shared station of two robots for pick and place tasks, featuring a combination of Scara and industrial robots.

Robots were connected to an OPC UA cloud server in these use cases. The cloud server enabled location-independent teleoperation of the connected robots by enabling accessible bidirectional communication. Figure 4.1 presents the architecture utilized in use cases one and two. Simulated models of these robot stations were created using Visual Components, and a custom Python script bridged the simulated models to the physical robots. During the use case development, engineers at Centria used the DT to operate and program the welding and pick-and-place robots physically located at UiT. The average read and write delays under 100 ms were measured between the endpoints during evaluation. The detailed results are presented in publication II.

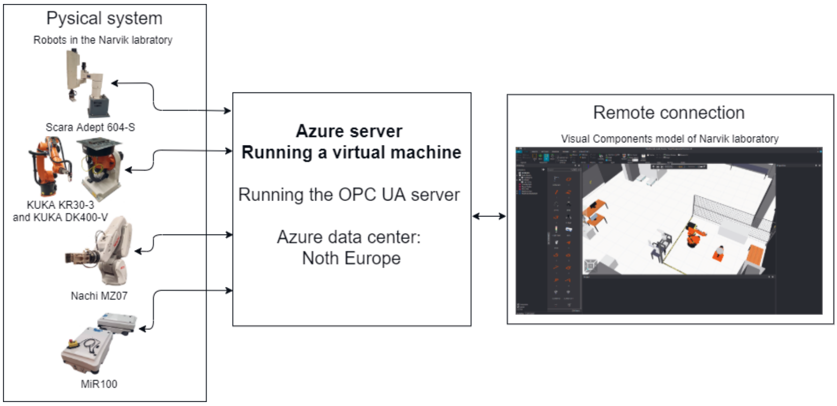

Figure 4.1 Architecture of the initial throwaway prototype (Publication II)

The third use case enabled remote training in basic robot control and programming. The physical twin consisted of an industrial robot mounted on a table. The robot had an electric spindle to engrave figures onto the precut wooden stock. DT of the robot cell was based on a RoboDK simulation. The bidirectional communication was implemented using the RoboDK driver and a specific program running in the robot controller. To evaluate the third use case, the DT was piloted as a part of a remote robotics training course Centria organized for the students of UiT during the COVID-19 pandemic.

This part of the course consisted of seven tasks, starting from building a digital model of the physical robot cell located at Centria and ending with testing milling trajectories remotely on the physical robot utilizing the DT created by each student. The use case enabled the students to create and utilize a DT of a robot cell. While this use case enables the creation of a simple DT for a single robot, the approach was unsuitable for simultaneous connections to multiple controllers and is limited to specific software products. Furthermore, the DT did not provide any CS means and is, therefore, unusable.

The main result of this publication was the conceptualization of the common platform, based on the aforementioned key findings "Common DT platform utilizing open communication standards is required for education, training, and collaboration of robotics". The key findings of this publication were: 1) DTs utilized for collaboration between organizations require an open platform and open communication protocols, enabling efficient cross-platform and cross-organization usage, and 2) DTs are suitable tools for collaboration in research, education, and industrial applications.

4.3 Publication III: Evaluation of cybersecurity in agile manufacturing: Maturity of Technologies and Applications

The third publication evaluated eighteen use cases to define the level of CS in agile manufacturing. Furthermore, an overview of state-of-the-art CS initiatives and standards for the manufacturing industry was presented. The evaluated demonstrators were use cases of the TRINITY DIH [95], aiming to provide SMEs with methods and tools for agile manufacturing. Sixteen use cases focused on robotics, while the remaining two focused on IIoT applications. Data for the evaluation was collected by preparing and distributing a questionnaire to the TRINITY DIH participants.

After receiving answers to questionnaires, the data was presented in structured tables. The results indicated that none of the use cases were designed to be cybersecure, and CS was considered an issue in only four use cases. Since CS was not considered during the design of the use cases, improving CS would require re-designing and re-implementing the use case from scratch. The results indicate weak awareness of CS among partners of the TRINITY DIH; partners were encouraged to migrate to more CS components and services. The NIST framework [107] provides a roadmap to reduce CS risks for the manufacturing industry and can be utilized to re-design the use cases.

The main result of this publication were the methods to assess CS to increase the technological maturity level of the common DT platform prototype, presented in publication IV. The key findings of this publication are: 1) CS requires consideration during the design phase of an application, platform, or framework, and 2) CS is a key enabler for online platforms, cyber-physical systems, and DTs.

4.4 Publication IV: Common Educational Teleoperation Platform for Robotics Utilizing Digital Twins

Publication IV presented a prototype of a common teleoperation platform for robotic applications. The prototype is based on open-source software and designed following the CS guidelines presented in publication III. The presented platform enabled social communication, video streaming, and sharing of available resources.

The requirement specification table, presented in section 2.1 of publication IV, provided a guideline for the system architecture and implementation of the platform. Functional requirements are divided into two levels depending on how important the requirement is, and the levels defined are must and could. The non-functional requirements are related to quality and are divided into three subcategories: usability, security, and performance. The requirement specification was defined by the authors of publication IV, who have experience in teaching, software engineering, robotics, and system administration.

The platform was developed in collaboration with Centria and UiT to provide an environment for robotic education, training, and collaboration. DTs were essential components of the platform; all physical systems connected to the platform featured a digital counterpart and a bidirectional communication layer to enable automated data flow between the twins. The connections and services of the platform are presented in Figure 4.2.

The most important service on the platform was the MQTT broker, which enables a low-level communication layer. The communication layer enabling data exchange between the physical twin and DTs utilizes two mainstream communication protocols: MQTT and OPC UA. MQTT was the primary communication protocol of the platform, enabling end-to-end messaging between the user device, the cloud server, and the robots. The MQTT broker [63] on the cloud server was configured to require authentication and encryption of the messages to enable cybersecure communication. MQTT enables low-latency communication by utilizing publish-subscribe messaging.

Local servers in the UiT and Centria laboratories provided a bridge between MQTT, OPC UA, and proprietary protocols. The OPC UA to MQTT bridges on the proposed platform were implemented with Open62541 [93] or a combination of FreeOPCUA [37] and Paho [6] open-source implementations of the OPC UA and MQTT. In addition to the communication broker, services required for teleoperation were DT and video streaming. The implemented DTs were primitive, written in a scripting language to maintain low latency. Physical limitations of the robots were defined in the DTs to enable validation of the user trajectories before commissioning on the physical system. The primitive DTs did not feature collision avoidance.

The web-based user interfaces were developed utilizing the Node-RED flow editor [28]. User interfaces enable jogging the robots in linear and PTP modes, creating simple programs, and running the created programs. Slider, gauge, and button interface elements enable teleoperation functionality. The web-based user interface also included a video stream of the teleoperated robot. Figure 4.3 presents the web-based user interface.

The platform presented was not restricted to the teleoperation of robots

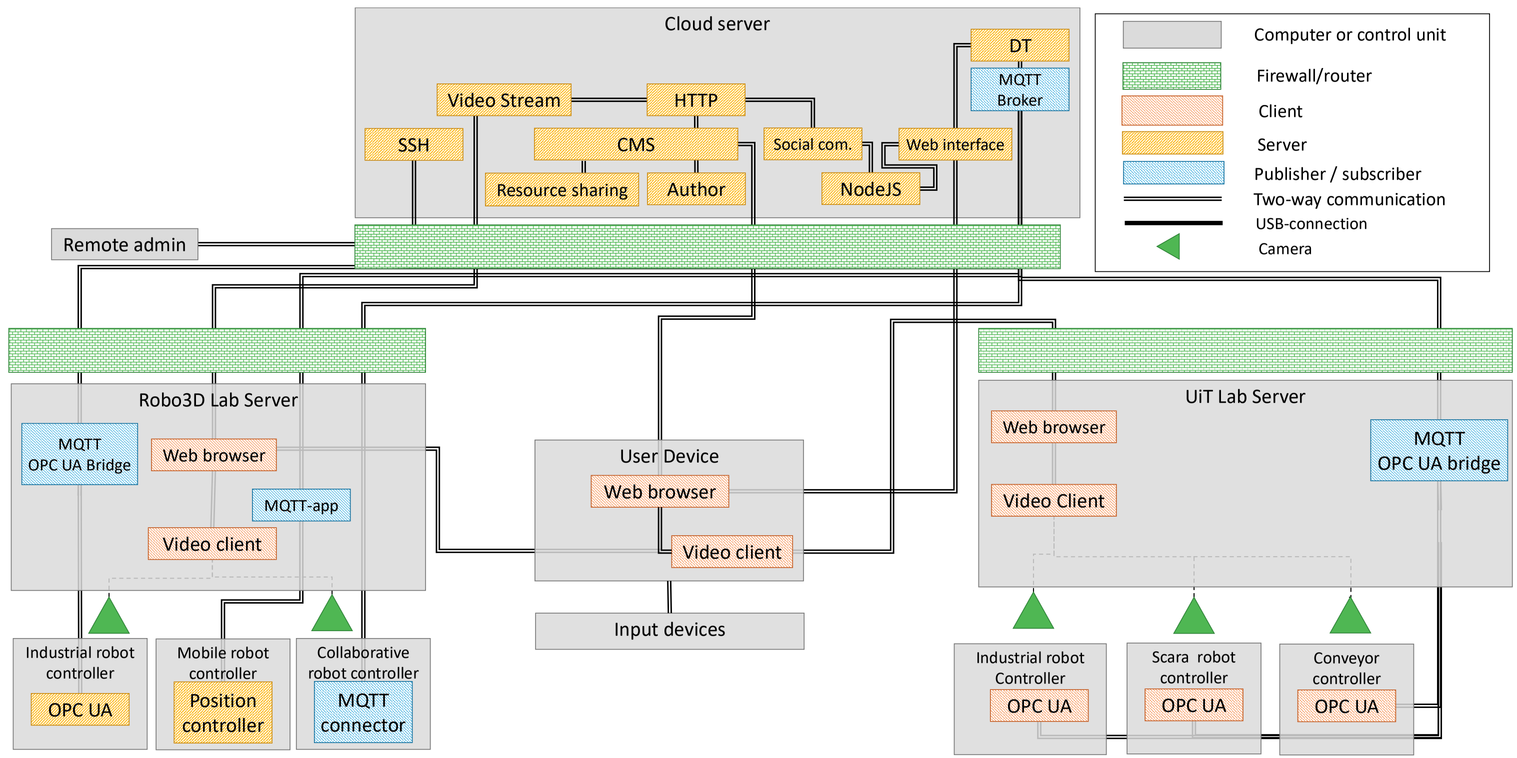

Figure 4.2 System architecture of the common DT platform (Publication IV)

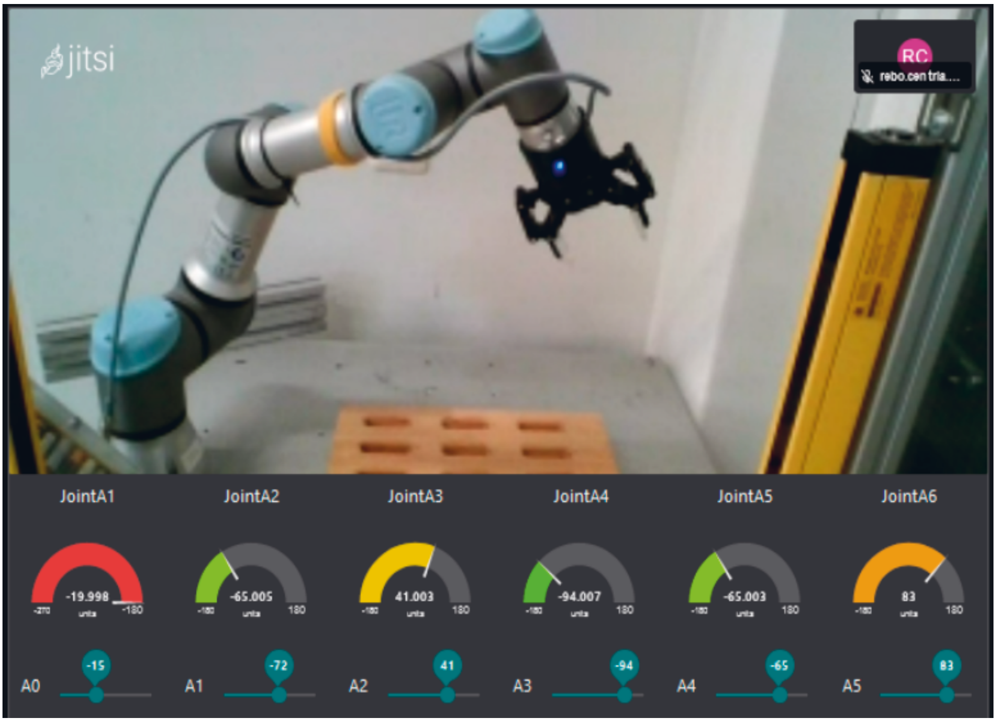

Figure 4.3 Web-based teleoperation user interface (Publication IV)

since connecting any system with an Ethernet connection was possible. For example, the teleoperation of a conveyor system was enabled on the platform. Furthermore, the platform enables the teleoperation of industrial, collaborative, and mobile robots. The platform's functionality was validated by defining and conducting high-level tasks for each connected system. The cloud server and local servers were behind a firewall, configured only to allow ports mandatory to connect to services on the platform.

The firewall enabled connections for DTs, web interface, video streaming, and remote administration console services. In addition to restricting ports, the firewall restricted geographical access to clients from Finland and Norway to minimize the number of potential cyber attacks. A CA-certificate provided by GEANT [114] was utilized to encrypt the data transfer. The initial vulnerability scan before configuring the services and firewall is presented in Appendix C.

The main results of this publication are the architecture and requirement specifications for the common DT platform and the prototype of the cybersecure common DT platform. The key findings of this publication are: 1) MQTT and OPC UA are efficient communication protocols for DTs, and

2) The teleoperation platform utilizing DTs is suitable for robotics training and education.

4.5 Publication V: Digital Twins Utilizing XR technology as Robotic Training Tools

The fifth publication extended publication IV, replacing the primitive DTs with more sophisticated implementations and providing high-level extended reality (XR) user interfaces for the teleoperation of the robots. In addition, the publication extended the research by evaluating the benefits and challenges of utilizing XR technologies in robotic training. Instead of the web-based interfaces to teleoperate the connected systems, VEs were proposed.

Three prototype VEs utilizing the aforementioned technologies were developed to evaluate the benefits and challenges of XR, VR, AR, and AV in robotic training. All the implementations were modeled using Blender and compiled using the Unity3D game engine. To enable cross-device compatibility and accessibility, WebXR runtimes are used. Three robot stations were modeled using Blender to create a variety of scenarios for robotic training. In addition, a virtual model of the Robo3D Lab was modeled to provide a container entity for the robot stations. The prototype VEs are presented in Figure 4.4

Figure 4.4 The prototype VEs from left to right: AV presenting augmented objects, virtual robot projected using AR and virtual safety training for large-scale industrial robot.

Three-dimensional models of the robot stations were imported to Unity3D to program the required functionality. The first training scenario utilized AV in a pick-and-place task. The VE consisted of virtual copies of the physical robot station, including an arm robot, gripper, and manipulated objects. The web cameras augmented the side, and top views of the robot reach area into the VE. The teleoperator, fully immersed in VR, had no way of knowing the positions of the moving objects, such as the position and pose of the objects he/she manipulated with the robot. The augmented video streams from the side and top views of the robot reach area provided the exact positions of the physical objects for the teleoperator. Unity3D asset provided by AVStack [42] enabled the projection of the two video streams on any texture in the VE. The high-level task defined for the AV implementation was to pick up three basic-shaped objects in the robot reach area and place the objects into precut holes of a cardboard box.

The second AR training scenario consisted of a small industrial robot, a gripper, and three basic-shaped objects. The prototype VE evaluated robotic training on mobile phones and tablets. The user could project the virtual robot anywhere to exercise or train in robotics and interact with the robot utilizing the mobile device's touchscreen. The virtual robot could be dragged from the TCP, and buttons overlaid on the side of the touchscreen enabled the user to open and close the gripper. Furthermore, a live video stream of the teleoperated robot was provided in the upper right corner of the touchscreen. An assembly task was defined for AR implementation as a high-level task. The goal was to stack the three basic-shaped objects. The challenge of this task was the robot's short reach distance, requiring accurate trajectory planning.

The third training scenario was an immersive VR environment for safety training; the VE was an evolved version of the virtual safety training presented in the publication I. The VE was a virtual copy of the large-scale industrial robot station, consisting of the robot on a linear servo track, robot tooling, safety devices to control the robot reach area, safety fences, and a floor structure. This VE enabled the training of working in collaboration with large-scale industrial robots during the floor manufacturing process. After the training, the trainee knew how to operate the safety laser scanners, light curtains, and microwave scanners. The functionality and visualization of the safety control panel were identical to the physical control panel. Physical fences and a wall behind the robot station surrounded the robot reach area.

Safety devices monitored three passageways in the safety fences. The safety laser detecting beams, non-visible in the physical robot station, were visualized in the VE. The two zones of the safety laser scanner for slowing down and stopping the robot when approached were also visualized in the VE. The visualizations gave the trainee an understanding of areas that are not permitted while the robot processes the floor structure. In addition to the safety-related aspects, training in synchronizing the manual labor processing phases with the robotized phases during manufacturing is possible. During implementation, it was decided not to stop the motion of the physical robot if the virtual safety devices were tripped; instead, only the virtual robot stopped, and after resetting the virtual safety controller, the virtual robot synchronized motion with the physical robot. The video stream of the physical robot was overlaid onto the top part of the VR view. In this VE, the integration level is a digital shadow; the robot was not teleoperated and instead ran a program for manufacturing in a loop. The VE was utilized for training the HRC.

The main results of this publication were AV, AR, and VR training environments for robotic training and education. The key findings of this publication are that VEs are not bound by physical constraints and can enable location-, time- and device-independent training in robotics.

5 RESULTS

This chapter presents the prototype of the common digital twin platform for education, training, and collaboration. The common platform utilizes DTs as tools, enabling users to interact with the robots in remote laboratories. Solving the research problem: *There is a barrier preventing physical access to the laboratory, so an alternative access method is required* by breaking the barrier of physical distance between the user and the robots. In addition, the results of a feedback survey are provided.

5.1 Prototype of common digital twin platform for education, training, and collaboration

The main result of this dissertation is the prototype of a common DT platform for education, training, and collaboration. The DTs of the common platform are the tools enabling the students, trainees, and collaborators to interact with the physical robots. The platform and the DTs enable access to the robotic laboratory, independent of the physical locations of the user and the robots. Figure 5.1 presents the physical and virtual environments of the platform and the communication layer between the two.

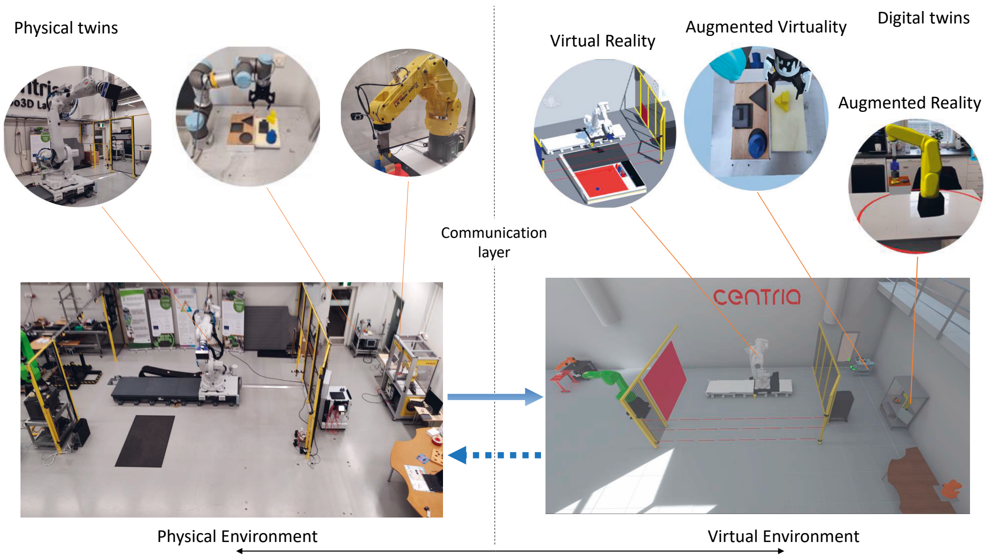

Figure 5.1 Physical and virtual environments and communication layer interfacing the two (Publication V)

The cloud server-based architecture enables worldwide access to the platform's services enabling education, training, and research collaboration in robotics. Seven robot stations and two mobile robots are available on the platform for teleoperation. Self-study materials for telerobotics, mobile, collaborative, and industrial robotics are available to gain knowledge in robotics. Self-study materials consist of theory on the aforementioned topics and practical exercises to gain basic robotics skills such as programming and controlling the robots.

The available exercises are the high-level tasks defined for validating the DTs, presented in publications IV and V. The self-study materials and exercises enable training in robotic-related skills and gaining knowledge in robotics. Furthermore, remote access to laboratories and the sharing of robotic resources enable collaboration between research organizations. High-level user interfaces utilizing XR enable virtual remote access to robotics laboratories, independent of device, location, and time.

The prototyping and piloting of the platform answer the research question 1: *In what manner a teleoperation platform utilizing DTs is technically feasible for robotics education and training?* The presented platform is technically feasible in the manner of low latency, accessibility, and stability. The low latencies of DT communication and video streaming enable efficient teleoperation and monitoring of the robots. In addition, the platform enables stable and accessible resource and content-sharing services.

5.1.1 Digital Twins

The second-generation DTs developed in publication IV are based on Unity3D Inverse kinematics [9]. DTs utilize the Jacobian matrix [16, 70] to convert Cartesian TCP to individual joint values and the Denavit-Hartenberg convention to convert Cartesian TCP to joint positions [82].

The inverse kinematics of Unity3D utilizes the included rigging, binding the virtual elements together using constraints similar to the physical twin. The IK calculations based on these constraints prevent moving the robot to out-of-reach or non-desirable positions. In addition to IK, colliders defined for the robot arm, gripper, manipulated objects, and stationary objects enable collision avoidance. The flowchart of the second-generation DT logic is described in Figure 5.2.

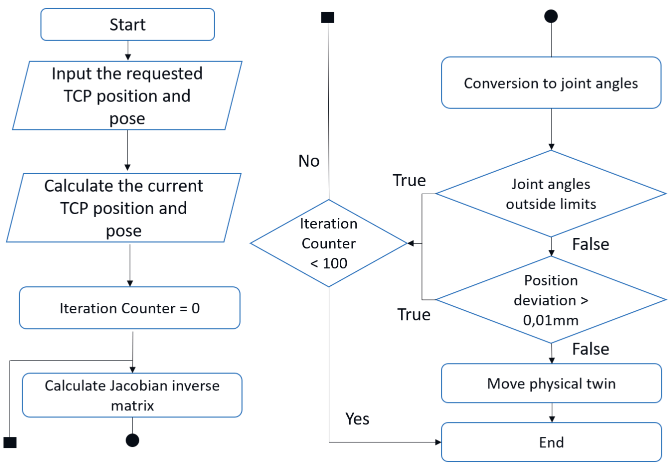

Figure 5.2 The logic of the second generation DTs (Publication V)

5.1.2 Communication layer

The communication layer connecting the DTs to physical robots is described in this section. The communication layer consists of the cloud server, physical robots, and local servers. Local servers at the Centria Robo3D Lab and UiT manufacturing laboratory connect the robots to the cloud server. The local servers share the local area network with the robots and connect to the robots utilizing a wired Ethernet connection and TCP/IP stack. The local servers host the OPC UA to MQTT bridges to interface the robots requiring OPC UA to MQTT bridges to the cloud server.

The individual robots connect to the platform utilizing either an OPC

UA client or an MQTT connector. In case the robot controller enables a native MQTT connector, the controller can connect to the MQTT broker directly. In case the robot controller enables native support for only OPC UA protocol, the robot connects to the cloud server through an OPC UA to MQTT bridge on the local server. An example of MQTT to OPC UA bridge is presented in Appendix A.

The purpose of the bridges is to interface robots without native support for the MQTT to the cloud server. The bridge receives MQTT messages and saves the positions required by the user into the robot controller OPC UA server variables. Furthermore, the bridge reads the current position of the robot joints and TCP from the robot controller OPC UA server variables and publishes the positions to the MQTT broker. The requested positions are received either as MQTT messages or variables on the OPC UA server, depending on which protocols are natively supported by the robot controller.

A custom robot program presented in Appendix B, running in the native runtime of the robot controller, is required to receive and process the teleoperator's required TCP or joint positions. The robot program receives the requested positions and creates a linear or PTP move to the requested position. In addition to positioning the robot, the functionality of the gripper is supported.

The message is a JSON formatted text containing the required attributes to connect the digital and physical twins; an example of a JSON message is presented in the listing below. The message's structure and attributes are identical on all the twins; only the values of attributes vary. In addition to MQTT, custom OPC UA to MQTT bridges are implemented if the robot controller does not enable native MQTT support.

```
{"roboPose":[-0.0193, -1.295, 1.426, -1.787, -1.5506, -0.597],
    "processProgress": 77.7,
    "counterData": 777,
    "processBusy": true,
    "gripperClose": false,
    "stationName": "Little Giant"}
```

5.2 Validation of the platform and survey feedback

The platform prototypes presented in publications II and IV demonstrated DTs to control robots in Finland and Norway. The prototype, presented in publication IV, evolved from the architecture presented in publication II.

The functionality of prototypes in publication IV was verified by defining high-level tasks for each twinned robot station. The authors of publication IV conducted high-level tasks on each robot station. Validation was considered successful if the user could perform the defined task utilizing the DT. After a few iterations and re-implementations, all the DTs passed the validation process. After the successful validation conducted by the authors, a pilot group participated in the course on DTs.

The pilot group consisted of about fifty engineering students participating in an online lecture on telerobotics. The students created user accounts on the platform and tested the platform's teleoperation, resource management, social communication, and video streaming capabilities.

To answer research question 2: *What are the benefits and challenges of utilizing XR technologies for robotics training?* The survey proves that the benefits of utilizing XR technologies are easy teleoperation and remote learning. Challenges are creating attractive user interfaces, exercises, and self-study material on the platform. Furthermore, bad Internet connection caused a poor user experience for one of the students. Table 5.1 summarizes the scored feedback and lists a few comments from the pilot group.

Table 5.1 Summary of the pilot group feedback

The Question	No	Not really	Yes	Quite	Very
Teleoperating the robots was easy?	5.6%	11.1%	50%	11.1%	22.2%
DTs enable realistic learning of basic robotics?	5.5%	22.2%	55.6%	11.1%	5.6%
I did learn something new about robotics?	0%	38.9%	38.9%	16.7%	5.5%
I could teleoperate the robots without any guidance?	5.5%	5.6%	27.8%	22.2%	38.9%
Free comment 1: The concept is new and interesting					
Free comment 2: I can move the robots from the home office.					
Free comment 3: Video stream and CMS worked well.					
Free comment 4: Please add more tasks for the robots.					
Free comment 5: Delays in the connection made it hard to control the robot.					
Free comment 6: The content could be more attractive visually.					

5.3 Cybersecure implementation

Authorization, authentication, firewall ruling, and encryption protect the platform services and DTs against cyberattacks. Users can register on the platform with a valid email address; the registration process is autonomous and forces the use of strong passwords and periodic changing of the password. Authorization provides three types of user rights: authenticated user, content editor, and administrator. The authenticated user is the base level enabling access to the platform services as a user without editing capabilities. Content editors can access the services and edit the webpages on the platform to create content such as learning materials. The administrator has full rights to administrative tasks such as upgrading and installing services, deleting user accounts, and defining user rights.

The firewall ruling allows only connections from Finland and Norway to access specific ports to utilize the services enabled on the platform. All the data transfers on the platform are encrypted, utilizing end-to-end cipher keys. Encryption protects the DT communication layer, social communication, self-studying, and teleoperation services. The platform has been online since March 2021, and vulnerabilities have been detected in OpenSSL library [85], HTTP server Log4j library [83], and in the firewall firmware [84]. All the CS issues have been detected by weekly vulnerability scans and fixed by reconfiguring and updating the services and firmware affected. Periodic vulnerability scans, updates, and configuration are mandatory to maintain the CS of the services. The vulnerability scan report of the platform is provided in Appendix D.

To answer research question 3: *What are the main CS challenges that might hinder the use of teleoperation in robotics?* The main CS challenges are new vulnerabilities detected in software components providing the services on the platform; attackers might exploit new vulnerabilities to gain access to a physical robot or disrupt other services on the platform. New vulnerabilities require constant monitoring of the potential issues and acting upon detected vulnerabilities.

6 DISCUSSION

This dissertation proposed a common digital twin platform for education, training, and collaboration. The main component of the platform is the cloud server, enabling all the services required for on-demand remote access to robots. This chapter discusses the benefits of the platform to Industry 4.0 and Education 4.0, the benefits of utilizing extended reality XR in robotics training, the cybersecurity challenges, and the limitations of the proposed platform.

6.1 The benefits to Education 4.0 and Industry 4.0

From the point of view of Education 4.0 and Industry 4.0, the proposed solution provides a common platform for education, training, and research for robotics. By enabling social communication, video streaming, resource sharing, teleoperation, support for mobile devices, and extended reality in a cybersecure manner, the platform fills the research gap mentioned in chapter 2.4. A network of educational institutions and industrial companies can create an open robotics platform to innovate and research robotics. The efficiency of manufacturing and education is increased by utilizing virtual environments independent of time and location to research, collaborate and study. Furthermore, providing a collaboration and learning environment natural to the digital native generation of today increases interest in industrial work by attracting the workforce to the industrial sector.

During the development phase of this thesis, the industry could have been more involved in the project to define the requirements for the platform. Input from the industrial sector was gathered during the setup of the training scenarios in Publications I, II, and IV. Unfortunately, the restrictions and isolation caused by the pandemic led to minimal communication during the requirements definition phase for the platform in publication IV.

6.2 The benefits and challenges of extended reality technologies for robotics training

The second prototype, presented in publication V, utilizes VEs to teleoperate the connected robots. Three virtual scenarios for training robotics were implemented to evaluate the benefits and challenges of utilizing XR. The benefits of virtual training environments are multifaceted and relate to the technology utilized; AV enables virtual teleoperation by augmenting the manipulated objects into the virtual world. AR enables mobility and robotics training independent of the trainee's time, device, and location. VR provides an immersive training experience when full concentration on the training is required. In the scope of this thesis, VR was utilized in training on HRC and related safety issues.

Next, an example is presented to analyze the added value of the remote possibilities. The analysis was not a part of the publications of the dissertation; analysis was performed together with the industry to analyze the benefits of XR robotics training to industrial companies. An example is a trainee working for a local building manufacturing company. The trainee does not have previous knowledge in robotics, and the training aims to learn skills in utilizing an industrial robot for an assembly task.

The trainee lives 30 kilometers away from Centria Robo3D Lab, and onsite training is arranged for a group of ten other employees of the same company simultaneously. To analyze time consumed on non-value added (NVA) and value-added (VA) activities, the flowchart in Figure 6.1 was drafted.

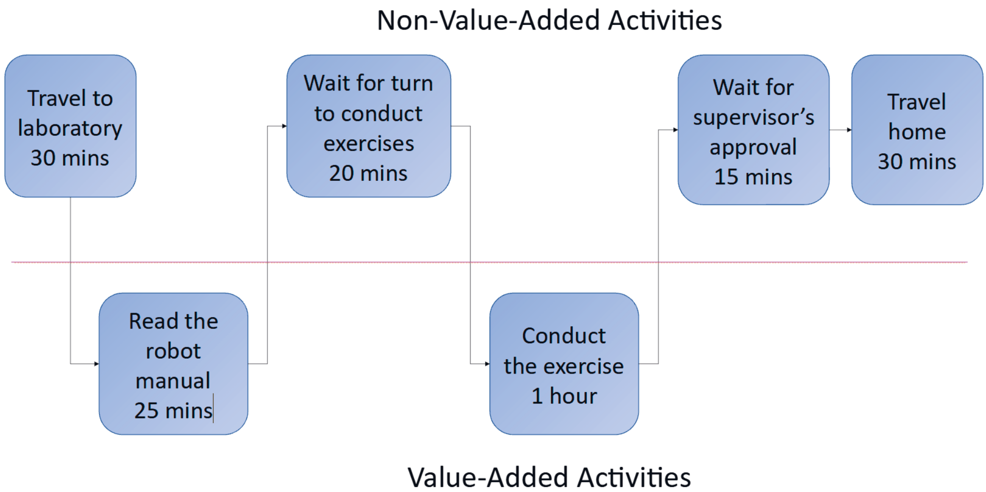

Figure 6.1 Value-added / Non-value-added flowchart of robot programming

Simultaneous on-site and remote training for an assembly task was arranged to provide empirical data about the time consumed in NVA and VA activities. Two of the six activities are considered relevant to train the new skill: Reading the robot operator manual and conducting the exercises. The four activities not adding value are: traveling to and from the training site, waiting for the turn to conduct the exercise, and waiting for approval from the training supervisor. All the non-value-added activities are not required to utilize the proposed platform.

Traveling is not required since the robot can be teleoperated, and the resource-sharing calendar disables the need to wait for turns to conduct the exercise. The supervisor approves the exercise, watching the video recorded by the trainee utilizing the video streaming on the platform. Remote training eliminates NVA activities, time, and costs for traveling. From a total time of 180 minutes, 95 minutes of NVA activities were eliminated.

The methods presented can be utilized to develop prototypes enabling the training of a broader scope of industrial equipment. The extended reality training environments can be applied to training operators for construction machines and larger entities such as renewable energy power plants. In addition, the DTs enable interaction with any system by establishing a communication layer to collect low-level sensor data and control the low-level actuators.

The challenge in utilizing XR in robotic training is the time consumed in virtualizing the existing entities, such as the laboratory environment and the DTs of the robots. For example, adding a new DT to the platform requires the modeling, rigging, and texturing phases before importing the virtual robot into Unity3D. In Unity3D, defining the kinematic and physical properties of the robot and programming the communication layer are required to create the DT. The process is time-consuming, and complete re-implementation is required if errors are made in the first steps.

6.3 The main cybersecurity challenges

An essential consideration for a common platform providing online services is finding the balance between accessibility and restrictions. Strict CS policy, laborious to the user, leads to abandoning the platform, and moderate CS leads to exploitation. The CS of the platform is only as strong as the CS of the weakest service on the platform. A platform consisting only of cybersecure components configured appropriately provides a robust and accessible DT platform; the challenge in setting up such a platform is to design the platform with CS in mind and set up periodic measures to confirm CS. The ultimate challenge of continuous work remains: maintaining CS requires periodic vulnerability scans and actions to update or replace vulnerable services.

To strengthen the CS of the proposed platform, an intrusion detection system (IDS) or intrusion protection system (IPS) [62] could be utilized. IDS and IPS provide rule-based active logging of malicious activity, and IPS has the functionality to block potentially malicious connections. In addition to weekly vulnerability scans, IPS and IDS can provide continuous real-time protection against cyber attacks [62].

6.4 Limitations and reflections

This section presents the limitations regarding the utilization of the proposed platform. The first limitation is the unsuitability for mission-critical control applications due to dependency on the internet connection. As the second limitation, the proposed solution does not provide haptic feedback to the user. Haptic feedback is mandatory in applications requiring hand-guided operations such as surgery [68]. The third limitation is that the proposed solution is unsuitable for telepresence; the microphones of the web cameras are disabled to guarantee the privacy of the persons present at the robotics laboratory, and no displays exist on the teleoperated robot stations.

Compared to hands-on training, the proposed platform limits to the predefined training scenarios since the trainee can not create, modify or add physical or virtual objects. The strength of the on-site training is enabling the trainee to create and modify the training scenarios; the only limiting factor is the creativity and imagination of the trainee. The trainee can construct or use any objects desired in pick-and-place or assembly training scenarios and create more challenging programming tasks if required.

The constructive research approach was chosen for this thesis, and as a result prototype of a common digital twin platform for education, training, and collaboration was implemented. The constructive approach enabled discussion and validation of the use cases' practical relevance and technical feasibility for online training, learning, and collaboration. The practical significance of this thesis is the main contributor to scientific relevance.

A more theoretical approach and methodology would have contributed to evaluating a common platform's scope, costs, usability, and learning effectiveness. The results of this thesis are on technical feasibility; a more theoretical approach could have provided more generalized information on the platform's suitability for different types of training scenarios and contributed directly to the scientific novelty.

6.5 Future work

In the future, multi-user support for the VEs should be added to enable simultaneous access to multiple users for social communication during training in XR. Allowing users to communicate during training and collaboration brings the virtual training experience closer to on-site training. The proposed DTs and VEs can be utilized as elements of the metaverse in the future, merging digital natives with industrial and educational training and collaboration platforms.

More educational institutions can join the platform to enable a broader selection of robot types. At this point, only industrial robots and a conveyor are available on the platform; adding a broader selection of robots, such as underwater and humanoid robots, would expand the selection of robots. Adding underwater robots and unmanned surface vehicles is planned to provide tools to pilot and prototype autonomous navigation algorithms and explore the aquatic ecosystem. The presented platform enables educational institutions to form an *Open robotics platform* for online teaching and education of robotics.

In addition, the platform will be integrated into teaching robotic courses to pilot and validate the pedagogical feasibility of the platform. An automatized feedback system will be developed to collect comprehensive feedback on the platform from the piloting students. The user feedback enables further development of the platform services, VEs, and the functionality of DTs.

7 CONCLUSION

This dissertation proposed a common digital twin platform for robotics education, training, and collaboration. The platform's architecture is based on the idea that DTs can be utilized as tools enabling trainees, students, and collaborators access to robots from distant locations. To support the claim *"Digital twins are suitable tools for robotics education, training, and collaboration",* practical implementation of a common DT platform was presented. In addition to the platform's architecture, extended reality user interfaces for teleoperation were presented, and the benefits of utilizing XR technologies in robotic training were evaluated. Cybersecurity is a key enabler for the proposed platform, DTs, and the low-level communication layer. The methods for cyber securing were presented and discussed in this thesis.

The proposed platform enables video streaming, social communication, content sharing, and the teleoperation of robots. Video streaming can be used to monitor the teleoperated robots or to augment real-world elements into the virtual world. Social communication enables chatting and arranging video meetings on the platform. Content sharing allows lecturers, trainers, and collaborators to share material with students, trainees, and collaborators. The platform's DTs enable users to interact with physical robots in two robotics laboratories: Robo3D Lab at Centria University of Applied Sciences, Finland, and the manufacturing laboratory at UiT, The Arctic University of Norway. While this thesis focused on robots, the DTs presented in this thesis enable connection to virtually any equipment supporting Ethernet connectivity and programming a communication application. Furthermore, geographical connections are not limited to Finland and Norway; connecting facilities worldwide is possible.

This dissertation evaluated and discussed the benefits and challenges of utilizing XR technologies in robotic training. The XR prototypes implemented have high-level user interfaces for teleoperation and monitoring of the robots connected to the platform. The benefits depend on the XR technology utilized. Virtual reality enables an immersive experience and the feeling of being present. The immersive experience is beneficial if concentration on the training task is preferred and the specific VR headset and hand-held controllers are available. Augmented reality enables training in robotics using mobile devices. AR is not an immersive experience; the virtual robot is projected into the real world utilizing the display and camera of the mobile device. AR enables location and device-independent training in robotics. Augmented virtuality is a reversed AR technology, enabling augmented real-world objects into the virtual world. In this thesis, AV was utilized to project moving objects from the table of the physical robot to the immersive VR training scene to enable teleoperation. Teleoperation of a robot utilizing an immersive experience is possible if the teleoperator can visualize the objects he/she is moving with the robot.

The purpose of the DTs is to enable the teleoperation of the robots on the proposed platform. Two DT implementations were utilized on the platform and presented in this thesis. The first-generation DTs are primitive, enabling only the features necessary to teleoperate the robots and validate the user-generated trajectories before execution on the physical robot. The second-generation DTs are more sophisticated, featuring collision detection, the Denavit-Hartenberg convention for Inverse Kinematics calculations, and forward kinematics calculations. The first-generation DTs use web-based user interfaces to provide a low-latency solution. The processing of IK and collision calculations featured on the second-generation DTs are utilized with the XR user interface to provide more precise collision avoidance and verifying.

The proposed platform and DTs enable education, training, and collaboration in robotics. The proposed VEs provide a training environment natural to the digital-native generation of today, supporting the goals of Education 4.0. The VEs enable location and time-independent studying and training. Compared to traditional lecturing in the classroom, VEs enable the intuitive and risk-free option for safety training for industrial and educational applications. For industry, training and collaboration without physical boundaries saves time and financial resources because companies are not required to invest in robotics or send an engineer to distant locations to verify and test solutions.

The proposed platform enables remote testing and validation utilizing robots in collaboration with educational institutions or partner companies, utilizing their existing robotic resources. By using the resource-sharing service of the proposed platform, the need to reserve time for testing and validation is trivial. In addition to Education 4.0, the proposed solution supports the ongoing Industry 4.0 transition to increase productivity. Furthermore, enabling the multi-user capability in the future brings the proposed solution closer to the industrial metaverse.

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APPENDIX A MQTT TO OPC UA BRIDGE PYTHON CODE

```
import paho.mqtt.client as mqtt
import re
import json
import math
import asyncio
from asyncua import Client
from asyncua import ua

url = "opc.tcp://127.0.0.1:61510/ABB.IoTGateway"
namespace = "http://opcfoundation.org/UA/"
joint = [0,0,0,0,0,0]
xyz = [0,0,0]

async def abbWrite(wantedArray):
    print(f"Connecting to {url} ...")
    async with Client(url=url) as clientopc:
        nsidx = 2;
        tag1 = clientopc.get_node("ns=3;s=6700—
            —/RAPID/T_ROB1/user/recvPose")
        new_value = '[[50,98,56]]'
        dv = ua.DataValue(ua.Variant([str(wantedArray)],
            ua.VariantType.String))

def on_connect(client, userdata, flags, rc):
    print("Connected with result code "+str(rc))
    client.subscribe("abbTopic/to/6700————")
\# The callback for when a PUBLISH message is received from the
server.
def on_message(client, userdata, msg):
    message = json.loads(msg.payload)
```

```
    global xyz
    if "roboPosetcp" in message:
        xyz_wanted = message["roboPosetcp"]
        a = 0
        xyz_string = "";
        pos_string = "";
        wantedXYZ = []
        for i in xyz_wanted:
            if a == 3:
                break
            xyz[a] = i
            a = a + 1
            print("Received_xyz:␣"+str(i))
            xyz_string += ","+str(i)
        a = 0
        print(xyz)
    if "roboPose" in message:
        joint_wanted = message["roboPose"]
        a = 0
        for i in joint_wanted:
            joint[a] = i
            a = a + 1
            print("Received_joint:␣"+str(i))
            pos_string += ","+str(i)
        a = 0

client = mqtt.Client()
client.on_connect = on_connect
client.on_message = on_message
client.username_pw_set("———", "————")
client.connect("———", ————, 60)
client.loop_forever()
```

APPENDIX B   ABB RAPID ROBOT PROGRAM

```
MODULE MainModule
        VAR pos target:=[0,0,0];
        PERS robtarget wantedTarget:=[[],[],[],[]];
        PERS bool wantedGripper:=TRUE;
        PROC main()
                MoveL wantedTarget, v100, z50, tool0;
                IF wantedGripper = TRUE THEN
                        SetDO Local_IO_0_DO3, 0;
                        SetDO Local_IO_0_DO4, 1;
                ELSE
                        SetDO Local_IO_0_DO3, 1;
                        SetDO Local_IO_0_DO4, 0;
                ENDIF
        ENDPROC
ENDMODULE
```

APPENDIX C INITIAL VULNERABILITY REPORT

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0	0	14	2	43
CRITICAL	HIGH	MEDIUM	LOW	INFO

Vulnerabilities — Total: 59

SEVERITY	CVSS V2.0	PLUGIN	NAME
MEDIUM	6.9	154349	PHP 7.4.x < 7.4.25
MEDIUM	6.8	143449	PHP 7.3.x < 7.3.25 / 7.4.x < 7.4.13 Multiple Vulnerabilities
MEDIUM	6.8	149348	PHP 7.4.x < 7.4.18 / 8.x < 8.0.5 Integer Overflow
MEDIUM	6.8	158133	PHP 7.4.x < 7.4.28
MEDIUM	6.4	141355	PHP 7.2 < 7.2.34 / 7.3.x < 7.3.23 / 7.4.x < 7.4.11 Mulitiple Vulnerabilities
MEDIUM	5.8	142960	HSTS Missing From HTTPS Server (RFC 6797)
MEDIUM	5.4	142904	PHP 7.4.x < 7.4.12 DoS
MEDIUM	5.0	136741	PHP 7.2.x < 7.2.31 / 7.3.x < 7.3.18, 7.4.x < 7.4.6 Denial of Service (DoS)
MEDIUM	5.0	144947	PHP 7.3.x < 7.3.26 / 7.4.x < 7.4.14 / 8.x < 8.0.1 Input Validation Error
MEDIUM	5.0	146311	PHP 7.3.x < 7.3.27 / 7.4.x < 7.4.15 / 8.x < 8.0.2 DoS
MEDIUM	5.0	140533	PHP 7.4.x < 7.4.10 Memory Leak Vulnerability
MEDIUM	5.0	155589	PHP 7.4.x < 7.4.26
MEDIUM	5.0	135969	PHP 7.4.x < 7.4.5 urldecode OOB Read
MEDIUM	5.0	11229	Web Server info.php / phpinfo.php Detection
LOW	3.3	139570	PHP 7.4.x < 7.4.9 Use-After-Free Vulnerability
LOW	2.6	153953	SSH Weak Key Exchange Algorithms Enabled
INFO	N/A	48204	Apache HTTP Server Version
INFO	N/A	45590	Common Platform Enumeration (CPE)
INFO	N/A	54615	Device Type

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APPENDIX D FINAL VULNERABILITY REPORT

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0	0	0	0	41
CRITICAL	HIGH	MEDIUM	LOW	INFO

Vulnerabilities   Total: 41

SEVERITY	CVSS V2.0	PLUGIN	NAME
INFO	N/A	48204	Apache HTTP Server Version
INFO	N/A	45590	Common Platform Enumeration (CPE)
INFO	N/A	54615	Device Type
INFO	N/A	18638	Drupal Software Detection
INFO	N/A	49704	External URLs
INFO	N/A	43111	HTTP Methods Allowed (per directory)
INFO	N/A	10107	HTTP Server Type and Version
INFO	N/A	12053	Host Fully Qualified Domain Name (FQDN) Resolution
INFO	N/A	24260	HyperText Transfer Protocol (HTTP) Information
INFO	N/A	50344	Missing or Permissive Content-Security-Policy frame-ancestors HTTP Response Header
INFO	N/A	50345	Missing or Permissive X-Frame-Options HTTP Response Header
INFO	N/A	11219	Nessus SYN scanner
INFO	N/A	19506	Nessus Scan Information
INFO	N/A	11936	OS Identification
INFO	N/A	117886	OS Security Patch Assessment Not Available
INFO	N/A	40665	Protected Web Page Detection
INFO	N/A	70657	SSH Algorithms and Languages Supported
INFO	N/A	149334	SSH Password Authentication Accepted

PUBLICATIONS

PUBLICATION
I

Digital twin and virtual reality for safety training

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Digital Twin and Virtual Reality for Safety Training

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***Abstract*—In this paper, our latest research related to digital twins and virtual reality environments for safety training purposes will be described and evaluated. We will present three practical use cases to outline the current maturity level of virtual reality technology for industrial environments. Two of our use cases are virtual reality applications for safety and emergency training scenarios. In addition, one use case is the implementation of a digital twin for off-site safety training. This use case presents a seamless real-time transfer of data between the physical and virtual worlds. Use cases were developed based on the needs of, and in co-operation with, local small and medium-sized enterprises (SMEs). The proposed affordable and simple approaches provide virtual safety training solutions that can be utilized by SMEs of different industries.**

I. Introduction

Modern industrial production facilities containing autonomous vehicles, collaborative and traditional industrial robots and fully automatic machines can seem very complicated from employee's point of view. This is true especially to new employees and trainees who have no previous knowledge of production arrangements. This lack of knowledge can lead to injury if the employee is not aware of important safety procedures. For example, if the operator of an industrial robot cell does not confirm that the robot cell area is clear of people before starting a robot, serious injury to a co-worker can occur. With an efficient safety pre-training, accidents caused by misinformation relating to correct safety procedures could be reduced [1]. Furthermore, if an operator has not been trained on how to act in an emergency, it can be fatal for an injured co-worker.

Traditionally safety training has been carried out by theoretical lecturing of safety procedures in an off-site classroom or on-site training in the production facility. Lecturing as a method for safety training does not offer a possibility for hands-on experience and previous studies have indicated ineffectiveness of traditional safety training compared to safety training in a virtual environment [2], [3]. The on-site training in the actual production facility is possible and effective method from the perspective of learning, however, not from safety's point of view as it can expose trainees to real dangers during the training. Hazardous situations can arise as the training is conducted in a real environment for employees who are not yet familiar with safety issues. Also a pause in the production is needed to carry out the safety training inside the work cells. From the company's perspective, this is a non-profitable way of training. The on-site training also causes stress to the instructor and trainees because they are interrupting production and are exposed to safety risks [2].

The idea of a digital twin was introduced by Grieves [4] almost 20 years ago to represent a concept of a virtual, digital equivalent to a physical product. The digital twin is a promising way to develop safety training to be more illustrative and efficient. The digital twin allows virtual entities to exist simultaneously with physical entities. The digital twin requires the connection between the physical model and the corresponding virtual model and the connection is established by using sensors to generate real-time data. He and Bai [5] have studied many aspects of the digital twin-based sustainable intelligent manufacturing in their comprehensive review. They found tens of different applications for digital twins, including product design, digital design and simulation, production process simulation, digital production line, equipment status monitoring, product service, fault warning and maintenance, and production index optimization. Most of the cases which they studied were from research organizations or large companies, not SMEs. Grube et al. [6] found that there is a huge group of SMEs that are struggling with identifying what I4.0 is in their context and how to make use of it. They proposed that learning factories will be a solution for SMEs to enable the utilization of I4.0 technologies, such as digital twin. Safety training should be part of this kind of learning factories.

Various industry sectors are in need of innovative safety training methods. This is the situation especially in the construction and mining industries which both are worldwide amongst the most unsafe industries [7], [8]. One innovative concept is the Safety Training Park [9], [10] where real-life situations are simulated through multiple methods. Currently, there exist three safety training parks in Finland and one is under construction in Sweden. The cooperation with almost 100 stakeholders has contributed to the immediate success of the parks. However, COVID-19 has created problems as people cannot gather together to train real-life situations. Even if there is a possibility to give an introduction of Safety Park's actions remotely, it is far from the on-site experiences in the park. Real-life situations created with digital twin (DT) and virtual reality (VR) technologies can bring immersive experience remotely. It also allows a wider audience from several workplaces to participate in the training.
Safety training solutions utilizing cognitive infocommunications possibilities such as VR offer an efficient alternative for traditional training [11]. Training in a virtual environment can be conducted off-site causing no pauses in the production nor exposing trainees to hazards. The virtual environment also enables risk analysis and safety planning at early design phases of a new production cell [12]. Furthermore, virtual environments offer almost hands-on experience for trainees. The virtual safety training can also include realistic training

for emergency scenarios like fire, explosion, or co-worker injury [13].

II. Related research

In the past, VR was mainly used for entertainment purposes, however, immersive technologies are nowadays used in different industries. VR based visual learning offers effective ways for training new skills [14], [15], [2], [16]. VR spaces, in general, are extremely useful generic tools for supporting learning and memory management that are important aspects of cognitive infocommunications [17]. Multiple examples of using MaxWhere 3D VR platform have been presented in literature [18], [17]. These examples assure that VR systems provide multiple ways that can be used for activating cognitive processes and improving inventive thinking. In addition, combining VR to DT provides possibility to view the inside that can include manufacturing simulations. The potential of using DT simulations with VR in manufacturing is not fully uncovered [19], [2], [20]. Combining VR and DT has been found successful for both industrial robot control and simulation [19], and for VR synchronization of a workshop digital twin [20]. One new approach for VR safety training is using panoramic augmented reality (AR) to develop a training environment [21].

The construction industry is one of the most unsafe industry fields worldwide [3], [8], [9], [22]. Construction is inherently dangerous when moving and handling heavy loads in unstructured environments. The construction work is a fragmented environment, where various factors are involved and many activities occur simultaneously. In addition to its high risk of accidents, the construction work contains several physical load factors that might affect the ability to work. Virtual environments for safety training purposes in the construction sector have been explored widely [3], [22]. Moore and Gheisari [22] analyzed in their recent review 46 virtual/mixed reality (VR-MR) applications in construction safety literature over the last decade. Their analysis showed that VR is the most dominant type compared to technologies belonging to the MR spectrum. Education and training are the most common reasons of the VR-MR for safety applications, and the majority of researchers applied VR-MR technology as a tool for improving hazard identification skills, followed by the hazard avoidance and hazard response, and communication. Examples of VR-MR and three-dimensional (3D) game-based training systems show that these technologies have a potential for improving construction safety [23], [24].

Rice [25] stated that keeping workers safe in the construction work is a dangerous game. He presented that realistic training scenarios are essential to increase the safety in construction work and VR training can solve many of the safety issues inherent in the traditional safety training. According him, VR provides a safer training environment, and it can bring ability to create (virtually) riskier and more realistic training. VR training allows a possibility for endless repetition and it can generate the randomness typical in real life. It provides a safe environment to test and evaluate procedures. Immersive VR training can increase trainees' focus and provide better evaluation tools for trainers. The training can be customized for specific sites and scenarios. VR provides more efficient training as it indicates a higher retention. One of the main benefits is that VR training lowers the training costs.

Mining is another industry field where safety training should be an important issue due to the dismal accident records [7], [26]. One common problem for mining is how to provide effective safety related training. Tichon and Burgess-Limerick [26] showed in their review that VR simulation offers the opportunity to develop perceptual expertise, perceptual motoric skills, and cognitive skills such as problem-solving, and decision-making under stress, without exposing trainees or others to unacceptable risks. Their conclusion was that there is potential for virtual environments to be effective in the mining industry. Examples of virtual safety training for mining were presented in studies of Liang et al. [27] and Al-Adawi and Luimula [28].

III. Software and devices utilized

A. SteamVR

SteamVR (Valve Corporation, Washington, USA) is a publishing and distributing platform for virtual reality software. SteamVR provides a connection between the virtual reality software and hardware [29]. The hardware for interacting with SteamVR are HTC Vive headset, two base stations, and hand-held controllers [30].

B. RoboDK

RoboDK (RoboDK Inc., Montreal, Canada) is a development platform for industrial robot offline programming and simulation [31]. RoboDK has support for over 200 different industrial robots from known manufacturers such as ABB, Kuka, Adept, and Kawasaki. RoboDK includes support for an online connection of robot systems and connection to the SteamVR platform.

C. Unity

According to Unity (Unity Technologies, San Francisco, USA), the Unity game engine is a framework offering possibilities to import visual model files in various formats, create scenes based on these model files and apply logical functionalities into these scenes [32]. According to Sim et al. [2], Unity is the most widely used game engine with a wide developer support network.

D. HTC Vive

HTC Vive (HTC Corporation, New Taipei City, Taiwan) is a virtual reality headset created originally by Valve and HTC [33]. HTC Vive integrates a gyrosensor, accelerometer, and laser position sensor to track head movements. Vive also includes base stations installed externally to track user movements in a real environment and hand-held controllers for user interaction in VR environments [30]. These devices together with SteamVR platform enable a full virtual reality experience.

E. Quuppa Intelligent Locating System™

Bluetooth 5.1 (Bluetooth Low Energy, BLE) includes direction finding feature that has been utilized successfully for centimeter accuracy indoor positioning. Quuppa Intelligent Locating System™(Quuppa Oy, Espoo, Finland) is an indoor positioning system (IPS) based on Bluetooth Low Energy (BLE) and detection of signal's angle of arrival. This technology can be utilized to improve the safety of robotized environments. With an accurate IPS, either mobile robots or people can be tracked.

IV. Experimental Results

A. Safety training based on VR model of a production cell

This demonstration aims to provide a VR experience for an offline safety training purpose. The demonstration utilizes intra-cognitive and inter-cognitive communication modes with a sensor-sharing communication [34], offering participants a shared audiovisual VR experience. The virtual environment is a model of highly automated large-scale production cell for a building element construction. The virtual environment is based on three-dimensional computed-aided design (CAD) models of the floor structure components, a gantry robot, and tools needed for processing. The Unity game engine platform is utilized in assembling the model files into a scene and adding a functional logic to build the VR experience for training purposes.

The robot cell consists of the following components

- gantry robot where industrial robot is installed hanging downwards,
- building floor structure as work piece, and
- robot tools needed for processing floor structure.

The robotized manufacturing of the floor structure consists of the following tasks: nailing of wooden elements, milling the route for the floor heat piping, and adhesive dispensing between the floor layers.

Each process described earlier is done in collaboration by a human and robot. The robot performs tasks requiring physical strength such as lifting heavy floor plates, the human worker takes care of tasks requiring visual estimation ability; for example accurate positioning of the plates before nailing. To guarantee safety of the human operator, laser safety scanners are installed on the robot and as the robot travels around the production cell, safety scanners create two invisible cone-shaped three-dimensional safety areas around the robot. Cone-shaped safety areas following dynamically the robot are different in size: the outer cone is larger and acts as a warning area to slow down the robot when interfered, the inner cone is smaller and acts as a stop area to stop the robot motion when interfered.

The VR experience enables trainees to visualize and learn their work tasks during the floor structure building process. Furthermore, it is possible to visualize robot safety areas that are invisible in the real environment. Triggering of the robot safety boundaries can be performed and possibility to pause and resume robot movements is provided for a better inspection of different tasks. Besides, a precise and close-up inspection of the robot processes is possible safely in the virtual experience. Figure 1 illustrates visualization of the safety areas. The outer warning area is shown in blue and the inner stop area is shown in red.

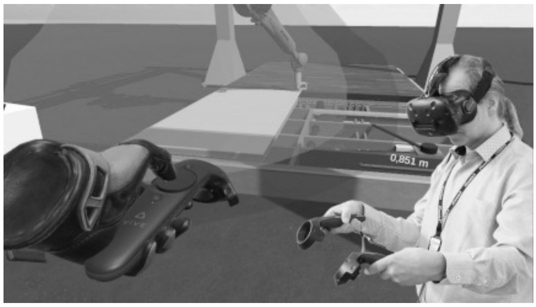

Fig. 1. Visualization of robot safety areas

The VR experience described provides a safe and risk-free way to study the following subjects: how to control a robot, phases of an assembly process, robot movement trajectories during process phases, their work tasks during certain processes, and functionality and physical position of devices securing their safety during the assembly process.

B. Safety training based on digital twin of a robot work cell

To provide even more realistic VR experience, this demonstration connects sensor information from machines to the VR experience. This demonstration utilizes intra-cognitive and inter-cognitive communication modes, sensor-sharing, and sensor-bridging communication described by Baranyi and Csapo [34]. The sensor information from humans and machines is linked together with RoboDK, SteamVR, and HTC Vive to provide a real-time digital twin of the actual production environment for training purposes. The digital twin presented here can be utilized for example to a virtual walk around the production facility and also training of specific work tasks. Because the actual production machinery such as robots and computer numerical control (CNC) machines have positional and operational state feedback connected to digital twin through RoboDK, the experience for trainees is very realistic.

Trainees and instructors can communicate with each other through built-in VR headset microphones and additional speakers. Additionally, trainees can move safely around the virtual production facility to learn movement cycles and safety distances around different machinery. The instructor can also participate in the virtual environment to instruct trainees, answer their questions and demonstrate certain work tasks for them.

The interaction with the virtual environment objects such as robots is carried out by users' physical movements and with hand-held controllers. HTC Vive base stations are able to track physical movement of the trainee within $4.5m \times 4.5m$ area. Moving longer distances is possible with the teleporting feature by aiming the hand held controller to a desired location and releasing a particular button.

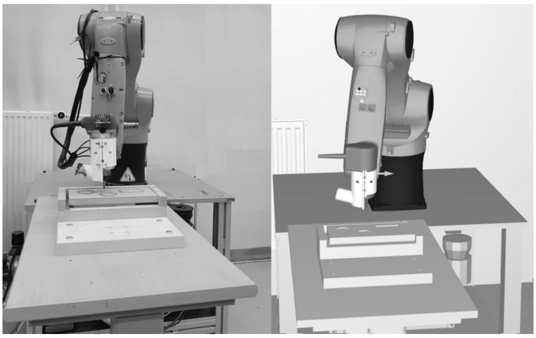

Fig. 2. Real environment vs Digital Twin

The digital twin described here is a virtual copy of the robotics laboratory at Centria. The three-dimensional model of the laboratory was created using a laser scanner and imported into RoboDK software to be used as an environment for adding CNC-machines and robots. The digital twin consists of five industrial robot cells and one CNC-machine cell. Robot cells are performing various tasks including: milling, nailing, welding, bin picking, and product testing. Figure 2 presents one industrial robot cell and the corresponding digital twin.

The purpose of this digital twin is to instruct students and visitors about safety procedures before physically entering the robotics laboratory. Risk-free virtual training of robots safety measures and work tasks is possible. During the training, attendees gain knowledge of how to: control robots, robot movement trajectories, robot reach areas, and safety devices specific for each robot. This concept can adapt to industrial environments with a small effort to realize any safety training in the virtual environment.

Quuppa Intelligent Locating System™was installed in the robotics laboratory (Fig. 3). The installation consisted of five locators evenly spread in the laboratory. Each locator was calibrated using three distinct points. The tracking is performed in real-time and spatial (x, y, z) positions can be "sensor" inputs to the digital twin. The system is not restricted to tracking people, instead it can be extended to mobile robots and other actors. Figure 4 presents method for linking human and machine sensor information from industrial to virtual environment by Quuppa and RoboDK for creating a real-time virtual twin.

C. VR based training for emergency scenarios

VR based safety training can be utilized in training personnel for a variety of possible emergency scenarios. This demonstration aims to create a realistic virtual experience for training mining workers in case of underground emergencies like fire, explosion or personal injury. The realistic simulation of fire and explosion in a real mining environment would be complicated or impossible to arrange in practice. A practical fire exercise in a real mining environment would require a lot of planning, arrangement of schedules, and setting up underground fire on purpose. This approach would expose trainees to hazardous situation. For these reasons, it is not a practical method

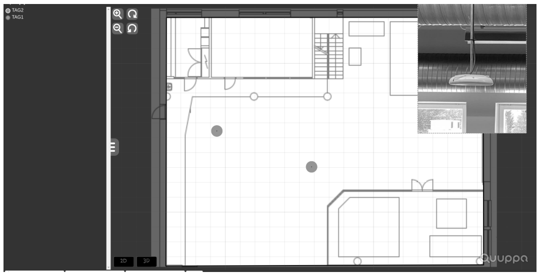

Fig. 3. Quuppa Intelligent Locating System™graphical user interface where two tags are tracked real-time. The inset shows one of the locators installed on ceiling.

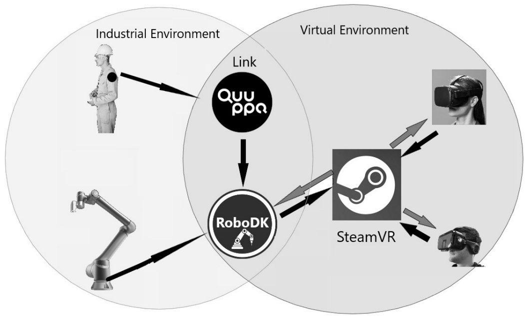

Fig. 4. Connections between virtual and real world

for a repeated training. Training for underground emergency scenarios conducted in a virtual environment is a risk-free and easy to arrange method. Training of one or multiple employees at the same time is possible. Also, repeating same exercises multiple times can be easily performed.

The virtual environment is based on a laser scanned point cloud of underground mining caves 400 meters below the ground. The Unity game engine is utilized here for building scenes and logic of emergency simulations. The scenes include the following emergency scenarios:

- fire,
- explosion,
- truck crash, and
- injured co-worker.

. In the actual safety training, trainees are instructed on how to act during emergencies. During the fire simulation exercise, trainees will gain knowledge on how the fire extinguishing peripheral is marked, located, and properly used. After completing the injured person scene, trainees know where to find first aid kits, how to use items included in the kit, and how to call paramedics to the scene. Trainees can interact within the VR by using hand-held controllers. Controllers allow trainees to move around the scene, grab and release objects, and utilize different objects. Interaction with the instructor and other

Fig. 5. Simulated emergency scenario

trainees is possible with a built-in microphone and add-on speakers.

There are many different scenarios in this virtual experience consisting of: mining caves, mining trucks, excavators, wheel loaders, fire equipment, and first aid kits. The main purpose of this virtual experience is to provide knowledge to personnel of correct procedures during possible underground emergencies. The lack of knowledge on how to act on fire at an early stage can cause rapid spreading of the fire and an uncontrolled disaster. Also if an injured co-worker is given first-aid immediately after the accident and paramedics are called to the scene as soon as possible, life of the co-worker can be saved. An emergency training scenario of a mining truck caught on fire is shown in Fig. 5

V. Conclusion

This paper provided three examples on how to conduct virtual safety training. Compared to the traditional lecturing and on-site learning, the virtual learning provides intuitive, stress-free and safe method for the safety training. Furthermore, it is possible to add visualizations of different aspects into the virtual world; safety scanner boundaries and safety light curtains were given as examples. These are invisible in the real production environment, but can be visualized and safely studied in the virtual environment. Virtual reality enables very realistic training of possible emergency scenarios, that would be challenging to simulate and implement in a real production environment. The digital twin provides almost hands-on learning of different work tasks in real time, without physically entering the production facility.

The use case demonstrations presented in this paper point out that virtual training provides an immersive, collaborative, and interactive learning experience. The virtual training provides a wide range of possibilities for various scenarios. The training is applicable from common safety issues such as areas in factories where to wear the helmet and safety shoes to training for very specific tasks such as working in a specific production cell. This type of virtual training provides not only a risk-free method for educating new employees before they enter the actual production facility but also a safe way of training of emergency scenarios. The successful use case demonstrations indicate that the maturity of the selected devices, software, and methods are on the level where also SMEs can utilize them flexibly and cost-effectively.

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PUBLICATION
II

Robot cell digital twins as a tool for remote collaboration between organizations

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Robot cell digital twins as a tool for remote collaboration between organizations

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Abstract— **"The whole is greater than the sum of its parts" is a common summation of Aristotle's famous thought. This phrase is now following reality. Working together has versatile advantages allowing us to examine things from divergent aspects and perspectives supported by the strengths of participating individuals. For complex tasks, simple digital platforms allowing to share documents, text, speech, and video are often not sufficient. Tasks including operation on sophisticated machines and other equipment are evident examples of this. These sophisticated machines are not necessarily physically available for everyone. However, digital alternatives of them can be. When connected with the physical world, enabling data flow in both directions and therefore implemented as digital twins, these systems allow true collaboration between people and machines independent of physical location. In this paper, digital twin implementations enabling efficient remote collaboration between two organizations are reported. These systems are not limited to research and education. Instead, utilization for remote deployment and maintenance tasks are possible.**

I. INTRODUCTION

Collaboration is a key to greater intelligence, problem-solving, and innovation than a single individual can achieve [1]. Through collaboration, we can combine our individual life-long experience and knowledge with others. This joint knowledge is a powerful asset in process of innovating new products, solving problems, and learning new skills.

Traditionally, researchers, designers, engineers, and students have gathered together in order to share and create new knowledge. Collaboration has taken place in conferences, design studios, workshops, and classrooms all over the world. Frequent traveling in order to physically meet has been self-evident to these individuals sharing the common passion. Meeting in a place where all individuals can physically meet and visually examine the prototype of a new product in its design phase, or to operate laboratory equipment in order to develop new skills have been a common practice.

However, during the last few years, some factors have led to reduced traveling activities. Climate change has increased our environmental awareness and changed our attitude towards traveling. Traveling is not an environmentally aware choice and therefore it should not be preferred. Restrictions and health risks due to the Covid-19 pandemic have also forced us to reduce traveling and find new methods for collaboration [2]. These factors restricting traveling to a common physical location in order to learn and innovate, have increased usage of online collaboration tools [3]. Online work and learning on theoretical exercises and tasks such as writing an article, essay, or solving mathematical equations is relatively easy due to online solutions such as Overleaf, Google Docs, and Microsoft Teams. These platforms enable real-time visual inspection of written text and equations for each group member. Online platforms may also provide chat or meeting tools and thus provide an excellent way for collaboration.

Work and learning tasks requiring visual inspection of physical world objects by all participants are more demanding. However, is it possible to replicate and visualize a physical world item such as a prototype of an aircraft or an industrial robot cell to each online participant? As an example, visualization of an aircraft prototype and its operational parameters are very important to a group of engineers trying to resolve possible obstacles before the product launch [4]. As another example, visualization of a robot cell in a university robotics laboratory is as important to a group of students learning robot programming. Designing an aircraft and studying robotics are both examples that require human collaboration - aircraft engineers combining their knowledge and experience in order to create the most efficient aircraft ever made, and students combining their knowledge and experience in order to learn new skills in robotics. These are both examples of a group of humans sharing the same objective and collaborating with each other in order to achieve the common goal.

A digital twin (DT) of an aircraft prototype or industrial robot cell enables visual inspection of components by each group member, independent of their physical location. The DT can replicate physical features of the aircraft or robot cell in real-time for online participants [5], [4]. Physical parameters requiring replication during a robotic exercise such as pick and place are for example speed and pose of the robot [5]. Conducting physical activity from a distance requires bridging the cognitive and sensor information between locations [6]. The sensor bridging is required to convert the robot's pose to visual presentation for an operator and to convert the operator's demand to the physical movement of robot joints.

The current technologies in Industry 4.0, such as the industrial internet of things (IIoT) and Open Platform Communications Unified Architecture (OPC UA), allow remote-

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controlled DTs. These systems can provide a safe interaction with the physical twin and give the operator remote control capabilities [7]. This allows people to control robots over large distances [8] which can be used for example in remote surgery [9] or remote learning and testing.

In this paper, we will present innovative implementations of two systems and experimental results on utilizing robot cell DTs as tools for efficient remote collaboration. These systems can be used for versatile applications such as education, training, deployment, and maintenance.

The rest of the paper is organised as follows. Section II is a literature review of the topic, Section III describes software tools used for implementing DTs, Section IV contains experimental results on using DT for robot cell collaboration between two remote locations, and using DTs for education, and finally Section V concludes the paper.

II. RELATED RESEARCH

Researchers and practitioners still do not agree on a unique definition of DTs. However, one definition of DTs is that they are virtual copies of the system that are able to interact with the physical counterparts in a bi-directional way [10]. Kritzinger et al. [11] pointed out that there is a distinction between digital models (not any form of automated data exchange between the physical object and the digital object), digital shadows (an automated one-way data flow between the state of an existing physical object and a digital object), and DTs (the data flows between existing physical objects and a digital objects are fully integrated with both directions). In the highest development stage, DTs seem to be promising enablers to replicate production systems in real-time and analyze them. In the literature, there are recent reviews that indicate that research on DTs is an active topic in various fields including manufacturing that is one of the most relevant topics [12], [11], [13], [10], [14]. According to [15] DT technology is now in third generation and is mature enough to combine individual objects and represent complete manufacturing plants, supply chains or smart cities. With deep learning DTs have ability to self-optimize and advance further autonomously [15] [16].

Digital twins should be capable to provide well-defined services to support various activities such as layout planning, production planning and control, monitoring, maintenance, management, optimization, and safety [11], [10]. However, the literature reviews show that the development of DTs is still at an early stage as literature mainly consists of concept papers. Tao et al. [13] claimed that current DTs are limited in the number of services offered and they are usually not totally integrated with the existing control system, and thus do not reach the full potential of DTs. Kritzinger et al. [11] argued that the results concerning the highest development stage, the DTs, are scarce, whilst there is more literature about digital models and digital shadows.

Robotic manufacturing is in many ways a specific area of the DT applications [17], [18], [19]. Many industrial robots have had for a long time in their robot programming software a possibility to use virtual controllers which are digital replicas of the real robotics system [20], [21]. Therefore, the robot work cells already have bidirectional control and feedback loops installed between the real work cell devices and the simulation tools or DTs. However, in DTs of robotic work cells, all the potential is not fully utilized, e.g. data analysis based on on-line data collection could be used more effectively for predictive maintenance [10].

The robot work cell DTs offer an excellent way for remote collaboration and deployment as well as a tool for collaborative distance learning. All these aspects have become more important during the time of the Covid-19 pandemic. Schluse et al. [22] introduced the concept of Experimental Digital Twin (EDT) as a new structuring element for simulation-based systems engineering processes and their interdisciplinary and cross-domain simulation. The basic idea of EDT suits well for remote deployment of robot work cells. As Tsokalo et al. [8] and Burghardt et al. [18] showed, virtual reality technology brings added value in this remote deployment process. Wuttke et al. [23] and Zacher [24] presented interesting case studies on how DTs of robot work cells can be utilized for collaborative distance learning.

III. DIGITAL TWIN SOFTWARE

Creating a DT of a physical world object is a process requiring a variety of software tools. Requirements of software depend on various parameters such as type of physical object, data involved, and the final purpose of the DT. Robot cell DT implementations presented in this paper require paired software on the robot controller and remote control PC. The software enables bi-directional bridging of cognitional and sensor information between the robot and its digital twin. In addition, the software enables the DT to represent the speed and pose of the physical robot in real-time and also enables the physical robot to convert the operator's demand to the physical movement of joints. Software utilized in experiments presented in this paper is described below.

A. Visual Components

Visual Components is a 3D manufacturing simulation software used to build and simulate factories. It has almost all modern robots and industrial relevant equipment such as conveyors, feeders, CNC machines, etc. Visual Components does also come with interactive VR for the simulation and built-in connectivity functions for example the OPC UA server.

B. RoboDK

RoboDK (RoboDK Inc., Montreal, Canada, https://robodk.com) is an industrial robot simulator and programming tool. RoboDK supports over 50 different industrial robot manufacturers such as ABB, Kuka, Adept, and Kawasaki. RoboDK also offers online programming capability and has plugins for major 3D-modeling software products, SteamVR virtual reality platform and OPC UA platform.

C. *KukavarProxy*

KukavarProxy (IMTS s.r.l, Taranto, Italy, https://www.imts.eu) is an open-source TCP/IP server solution. KukavarProxy enables reading and writing of Kuka robot variables over network. KukavarProxy was open-sourced since 2018.

D. *OPC UA*

Open Platform Communications Unified Architecture (OPC UA) [25] is a platform-independent communication standard (IEC 62541). It is scalable and can be used with an industrial controller but also enterprise systems such as manufacturing execution systems (MES) and enterprise resource planning (ERP).

E. *SteamVR*

SteamVR (Valve Corporation, Kirkland, Washington, USA,https://www.valvesoftware.com/en/) is a platform for publishing and distributing Virtual reality applications.

IV. Experimental Digital Twins

A. *Experimental digital twins for research collaboration*

This section describes two remote DT systems, a robotic welding cell, and a laboratory with different robots. For both systems, Visual Components are used as a control and programming interface.

The main component of these systems is the OPC UA server. In a previous project [26], all the robots were connected to the OPC UA server. This allows for monitoring and control of the robots through the same server. It can also be used to store information, such as a robot program.

The server was moved to a virtual machine on a cloud platform (Microsoft Azure server located in Ireland [27]) that allows connections outside the local network. This gives us a public IP address and makes it possible to access the server anywhere in the world with an open internet connection. The structure/connection of the system is shown in Figure 1.

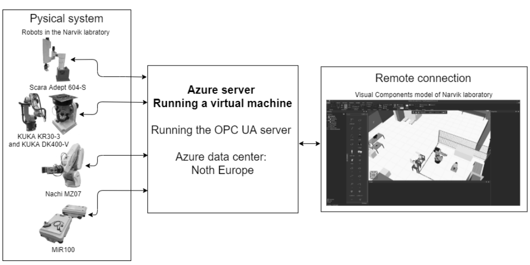

Fig. 1: IoT setup of the DT with the OPC UA server

To find the communication speed to the OPC UA server in Azure, a program was created that measures the time it takes to write and read a variable in the OPC UA server. The OPC UA server was running on a Azure virtual machine (D2s_v3) with Ubuntu 18.04. This test was performed in UiT in Norway and Centria in Finland and the average speed can be seen in Table I.

TABLE I: The table shows the average read and write time with the OPC UA server on Microsoft Azure

Communication speed		
Location	**Read**	**Write**
Norway:	61.74 ms	62.10 ms
Finland:	59.69 ms	59.48 ms

The communication speed (approx. 60 ms) is consistent with other tests [28]. Depending on the use case and the robot, this might not be fast enough for real-time control of robots.

The remote-controlled DT system is built on IIoT connectivity, where IIoT is used to improve production efficiency and effectiveness. However, using IIoT represents issues and challenges considering cybersecurity [29]. There are concerns considering authentication, control of access, privacy protection, and information management [30].

The benefit of using the OPC UA server and a cloud-based service is that you get a reliable platform and security without extensive development [31]. For example, the open-source OPC UA library used in this test has the Basic256Sha256 security policy built-in. A survey [32] conducted on the open-source library of the OPC UA standard showed that the security standard in the libraries is good.

In our experiment, four devices were connected to the OPC UA Azure server (Fig. 2): 1) Kuka KR 30-3 six-axis industrial robot, 2) Kuka DK400-V rotary table 3) Nachi MZ07 6 axis robot arm 4) Scara Adept 604-S 4 axis robot arm.

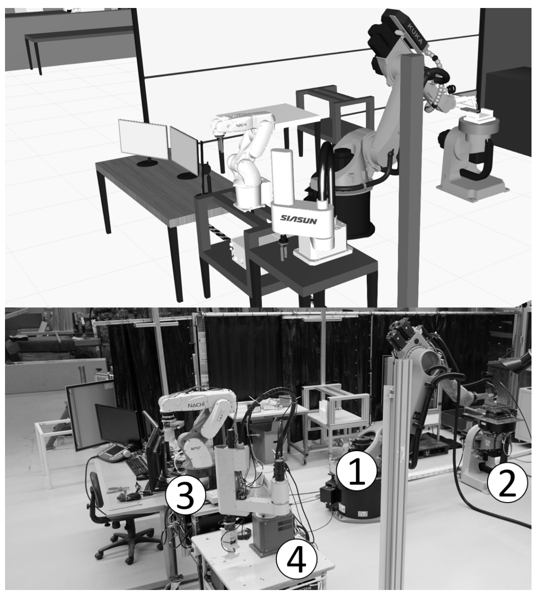

Fig. 2: Digital twin system, with the physical robot cell on the bottom and the digital system on the top.

The KUKA robot and rotary table are used for the robot welding system and the Nachi and Scara robots a part of the DT laboratory. Therefore, two experiments were carried out using the OPC UA server on Azure as the connecting point.

The first experimental system includes a set of robots that can all be controlled through the same server. As mentioned before, all the robots in the laboratory are directly connected to the OPC UA server. This allows for real-time control of the Nachi and Scara robots from the server. The same variables used to control the physical robots are paired to the same variables in the digital robot in Visual Components. This allows for direct remote control of all the robots with the OPC UA server as a middleware.

Since Visual Components is used as a programming tool, the robot programs can be tested in the simulation software before being executed on the real robot. When Visual Components are connected to the OPC UA server and simulation runs, the physical robot will imitate the same movement as the digital robot.

An experiment was performed where Centria in Finland operated Visual Components to control robots in Norway. In the test, both the Nachi and Scara robot were used. A program was created for the Nachi robot and executed on the physical robot. Afterward, a second program was made for the Scara robot and both the Nachi and Scara robot programs were executed simultaneously.

It should be mentioned that more robots can be added and controlled through the same system.

The second experimental system uses only the robotic welding cell, which includes the Kuka robot and rotary table, and welding equipment.

This system works similarly to the previous example. Visual Components was used to program the robots. However, in this case, robots were controlled in real-time through the OPC UA server. When the simulation runs, the program is automatically sent to the OPC UA server and stored in the server. This program can be executed on the physical system.

A second test was performed, where Centria in Finland used Visual Components to program a robot path to weld a line. The system is programmed by a remote user and then executed by a local operator. The program was first configured without turning the welding on, only the movement was performed to check if the movements were acceptable. Afterward, the welding torch was included and a line was welded.

Both experiments show us that a combination of the OPC UA server and the Azure server can be used to control multiple robots remotely over large distances. The DT laboratory experiment uses real-time control of the robots. This gives the remote user full control of the robot, but there is a delay that decreases the accuracy of the movement. With the welding system, the robot is programmed remotely and the programs are transferred to the OPC UA server. It is then executed using a computer directly connected to the robot and creates a more stable method to control the robot remotely in real-time.

B. *Experimental digital twins for education*

This section describes exercises for building and utilizing a robot cell DT as an educational example. The hardware of this system consists of 1) Kuka KR6 R900 sixx industrial robot, 2) Kuka KRC4 robot controller, and 3) remote control PC. Physically the robot and controller were located at Centria University, in Finland and the remote control PCs were located at homes of students in Norway. The robot controller and remote PCs shared the ethernet connection over the internet. Optionally the remote control PC can be equipped with a VR-headset and controllers, enabling an immersive VR-experience.

The software of this system consists of three components: 1) RoboDK simulation software running on remote controller PC, 2) KukavarProxy on robot controller in order to read and write robot variables such as joint position and speed, and 3) a specific program ”RoboDKSync” on robot controller [33]. The purpose of a specific program is to act as a bridge between KukavarProxy running on the robot controller and RoboDK running on the remote control PC. The program provides feedback of joint positions to RoboDK and receives commands from RoboDK. The overview of the main components and connections of the system can be seen in Fig. 3

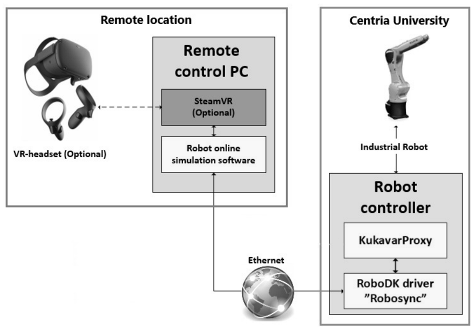

Fig. 3: Overview of RoboDK connection

The DT is a duplicate of the industrial robot cell at Centria University. The robot cell consists of the following components(Fig. 4): 1) Kuka KR6 six-axis industrial robot, 2) the robot pedestal and controller, 3) the milling head as robot tool, 4) the table with fixture and mechanism necessary for clamping a workpiece in place, 5) workpiece and 6) 360 Camera.

The exercise was divided into seven tasks. The first task in the exercise was to build a virtual duplicate of the physical robot cell. For this purpose, students were provided with 3D-model files of components and dimensional drawings of the robot cell described above. Drawings provided information on physical orientation, distances between components, and the tool center point location. The second task was to define the tool center point in a correct location, in this case to the tip of the milling cutter. The third task was the creation of milling trajectories on the workpiece. RoboDK has a built-

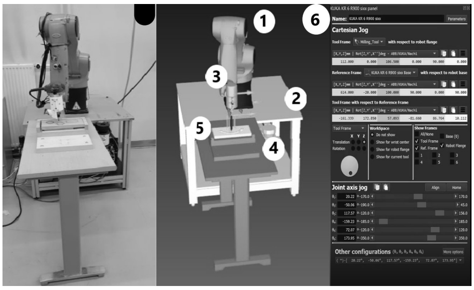

Fig. 4: Physical work cell, DT and remote control desktop view

in utility for generating trajectories based on features of a 3D-model. The fourth task was for the teacher to verify that the DT dimensions match the physical world. Mismatching dimensions or orientations may cause a robot to physically crash into a table or clamping fixtures, therefore this step is critical. The fifth task was establishing and verifying the connection between the robot controller and RoboDK. For this task, students were provided with the information necessary to set up a connection including the robot's public IP-address, username, and password. Once the connection was established between the robot and RoboDK, students were able to manually jog the robot either by using jog slider controls4 or by dragging the robot to the desired position with a mouse. Both the linear and point-to-point movements of the robot are possible. Manual jogging was task number six of this exercise. The seventh task was to run milling trajectories created earlier in the third step.

The presented exercise offers students an opportunity to create and utilize a DT of an industrial robot cell. It is a practical hands-on experience of a DT for future professionals. The solution presented here does not support multiple connections. Rather it is a simple point-to-point implementation when one robot cell remote control is required.

C. *Experimental virtual reality digital twins*

Visual components and RoboDK simulation software both support virtual reality environments and hardware. This enables remote controlling of industrial robot cells described in the previous sections also in virtual reality. Visual components and RoboDK offer VR-experience by supporting connection to the SteamVR-platform. The hardware for this experiment is similar to previous sections except that the optional VR-headset and controllers described in Fig. 3 are now connected to the remote control PC. Virtual reality provides an immersive and risk-free way of experiencing a DT. Virtual reality enables the examination of a robot cell from any viewpoint desired. For example, it is possible to examine the educational robot cell described earlier at close proximity. Virtual reality enables close inspection of robot cell details even when the robot is running, without a risk of injury. Fig. 5 presents virtual reality experience with the educational robot cell.

Fig. 5: Virtual reality view

Virtual reality provides an intuitive and immersive way of experiencing robot cell DT. Experiences in utilizing virtual reality as a risk-analysis tool have been positive [34]. Virtual reality is a potential tool also for safety training purposes [35], enabling a risk-free and realistic way of repeating hazardous situations as many times as needed.

V. Conclusions

In this paper, two different approaches for implementing robot cell DTs were presented: 1) DT implementation at Narvik based on OPC UA server and Visual Components simulation software as described in section IV-A, and 2) DT implementation in Ylivieska based on RoboDK simulation software and RoboDK driver component as described in Section IV-B.

The approach based on RoboDK and RoboDK driver is relatively easy to set up and therefore is a good solution for simple use cases such as educational exercise including only one robot cell described in this paper. The weakness of this approach is the lack of support for multiple simultaneous connections and support of only RoboDK as an interaction interface.

The system based on platform-independent OPC UA standard requires more work setting up OPC UA server and clients, but on the other hand enables a more broad range of simulations, ERP, and MES software. OPC UA is also capable of supporting simultaneous connections of multiple robots and controlling computers. When considering collaboration between organizations, an open system with more possibilities should be preferred. As a result, open systems enabling RoboDK, Visual Components, and many other software products as visualization and control interface are possible. Harmonized systems can be combined to provide an open platform for agile remote collaboration between organizations. DTs based on OPC UA are capable of providing connectivity between multiple organizations for remote collaboration. This open platform is not restricted to certain software products, instead, it allows any software supporting OPC UA as the client interface. Developing more intuitive methods for remote connections such as applications for mobile devices is also possible and should be considered in the future.

Based on experiments presented here: DTs can be used as tools for efficient remote collaboration in robotics research and education. Although, the experiments were performed in the field of research and education, using DTs is not limited to these fields. Instead, proposed approaches can be used as-is for different industrial tasks and applications. For example, they can be utilized for remote deployment, machine inspection, and maintenance reducing traveling costs.

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PUBLICATION
III

Evaluation of cyber security in agile manufacturing: Maturity of Technologies and Applications

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Evaluation of cyber security in agile manufacturing: Maturity of Technologies and Applications

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Abstract— **Utilizing Industry 4.0 technologies offers SMEs a possibility to increase productivity. Utilizing new technologies requires connectivity between production equipment, which raises Cyber Security (CS) issues that need to be addressed. In this work we analyse 18 demonstrators that are representative for different technologies and applications, and are of interest to the digitization of factories and agile production. CS analysis was performed by CS questionnaires to evaluate the current level of CS. As small and medium sized companies (SMEs), and researchers, may be unaware of CS issues, we provide general recommendations and measures to secure production systems from CS attacks.**

I. INTRODUCTION

In the past, industrial production systems were isolated and utilized networking protocols incompatible with IT-systems. Isolation from IT-systems provided protection against outside Cyber Security (CS) threats for production networks. However, during the last decades, demand for connectivity has driven industries to adopt common internet standards TCP/IP and Ethernet [1], [2]. Utilization of common internet standards enable trivial connectivity and data sharing between production equipment and the internet. As a downside, utilization of internet protocols require exposing industrial production systems to CS threats and attacks. Industrial systems set higher requirements for latency, speed and reliability, compared to IT-systems [3], thereby setting high demands for CS implementations.

Industry 4.0 technologies have proven potential to push industry towards growth [4]. Utilization of advanced technologies such as cloud computing, Internet of things (IoT), artificial intelligence, and big data are enabled by Industry 4.0. Exploitation of advanced technologies in smart factories require connectivity, exposing production machinery to CS risks, vulnerabilities and threats. Recent studies have identified CS threats as a risk to manufacturing and the digitalization of factories [5], [6]. CS attacks can lead to production shutdown, industrial espionage, information leaks and physical damages. CS is also a building block of physical safety as modern cyber-physical systems (CPS) enables intruders a possibility to cause physical damages and injuries. Thus, besides the technology itself, also physical processes, people, and even intellectual property [7] might be compromised by poor CS.

Different modes of operations for industrial and connected robots and systems start with controllers, following PLCs, ROS versions 1 and 2, IoT, and the Cloud. ROS version 1 was not designed with CS in mind, and CS is considered from ROS2 on [8], [9]. SMEs integrate the operation modes from ROS toward the newer features. The problem today is that reaching a sufficient level of CS can be too expensive for SMEs. Implementing high level CS requires investing into knowledge, devices and software products. The constant need for training of personnel, updating of devices and software tools, is too expensive for many SMEs. Therefore, SMEs may lag behind in the adoption of CS and measures taken to have a secure system. Fortunately, lately a variety of tools for the self evaluation of CS maturity levels are becoming available [10].

This paper presents a CS evaluation on selected agile manufacturing use case demonstrators of Horizon 2020 (H2020) project TRINITY[1]. Demonstrators present state-of-the-art solutions and are offered for European SMEs to adopt. CS evaluation is carried out with an evaluation tool created during the project. Results of the evaluation are the current CS knowledge level of each demonstrator and measures to take to improve the CS to a higher level. The contributions of this work are as follows:

1) Overview of the state-of-the-art in standards/initiatives towards CS in manufacturing
2) CS analysis of 18 demonstrators that offer technology and applications to make SMEs more agile in their production
3) Provide (general) recommendations for manufacturing companies and manufacturing SMEs in particular on practical steps to improve their CS

The paper is organized as follows. Section II presents a brief overview of current state of the art CS for production systems. Current standards, protocols and vulnerability assessments methods for CS are presented in Section III. The use case demonstrators and their CS analysis are presented in Section IV, and discussed in Section VI. The paper concludes in Section VII.

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II. State of the art

The current state of CS in smart manufacturing systems is reviewed in [2], [11], presenting important reported attacks against smart manufacturing systems and available active and passive countermeasures with their limitations. A comprehensive overview of CS in robotics applications is presented in a recent review [12], covering different aspects, such as vulnerabilities, attacks, countermeasures, and recommendations. Interesting reviews of CS in other specific application areas have also been published. In particular, CS for industrial control systems [13], [14], digital manufacturing [15] and the Internet of Things [9] has been reviewed widely. An overview of robot hazards [16], security modelling of autonomous systems [17] and social robots [18] help in outlining CS for robotics.

Technical evolution has recently reshaped the horizon of CS. In the past, the focus of CS was to protect company networks from outside access. Restriction of networks were implemented by firewalls, malware protections and intrusion detection systems [19]. Today, connectivity of devices and networks have enabled possibilities for location independent working and company servers are now running on cloud servers rather than inside factory premises. Working remotely with mobile phone or laptop is now possible and convenient, and flexible data sharing across supply chain enables new possibilities for SMEs production [19]. Remote working, cloud services and data sharing across supply chain requires access to company network from any location. Remote connectivity sets new challenges for CS, instead of yesterday's complete restriction selective access is required today. IT-management is forced to find a balance between security and flexibility, as firewalls and intrusion detection systems need a complicated set of rules in order to allow authorized access and to block unauthorized access. AI based intrusion detection systems are utilized for dynamic and effective network monitoring [19]. Honeypots are one CS solution for intrusion detection and can be set up to mimic any industrial control device such as PLC, robot controller or IoT-device, working as a decoy to draw the attention of an hacker [2], [20]. Eventually, after logging enough information about his activity and identity, a hacker could be revealed. Most honeypots have been implemented virtual or physical physical [2]. A Virtual honeypot is software running on the cloud or on a local server. A Physical honeypot is a physical device, such as a PLC dedicated for this purpose [20]. Lately also hybrid honeypots have been implemented to combine the best qualities of physical and virtual honeypots [20].

III. Cyber security in manufacturing

When looking for a method for analysing and securing a manufacturing system, protocols and standards provide basic guidelines for security, and vulnerability assessment determines current CS level of the system.

A. Protocols and standards

Development of manufacturing applications and the integration of CPS requires conforming to standards on safety requirements, as set by the Machinery Directive 2006/42/EC. ISO 13849, specifies general principles for design and validation, including a risk assessment executed by the manufacturer of the machinery. Functional safety of electrical, electronic, and programmable electronic control systems are covered by industrial standards IEC 62061. Both standards are inspired by IEC 61508 that addresses the functional safety of electrical, electronic, and programmable electronic safety-related systems. In addition, and most relevant to this work, IT security for networks and systems, is defined by IEC-62443 a standard for industrial communication networks. While seemingly separated, all safety related concerns affect one another, as a CPS operates as a single entity. ISO/IEC 27002 describes good practices and recommendations about information security. This standard was utilized by French National Cybersecurity Agency ANSSI for establishing good CE practices checklist [2]. ISO/IEC27002 does not cover cloud service CS. Good practices for cloud service providers and users are defined in ISO/IEC27017. According to [2] Microsoft Azure, Google Cloud Platform and Amazon Web Services follow ISO/IEC27002 and ISO/IEC27017 standards.

Architecture is the foundation of all functionalities the system can provide. Therefore, security should be initiated from the base of the system. Secure Architecture for Industrial Control Systems (SANS) is a reference architecture for industrial control systems focusing on access control, log management, network security and remote access. It proposes an architecture for the infrastructure of an industrial control system [21]. Other examples of how to secure an industrial control system are NIST 800-82, which covers systems containing distributed control systems (DCS), supervisory control and data acquisition (SCADA) and systems with PLCs and related programmable logic controllers. The NIST standard is utilized in discrete manufacturing, for example automotive and aerospace manufacturing industries [1]. NISTIR 8183, cyber security framework (CSF) [22] describes how to improve CS of existing manufacturing system. Concentrating on the following five functionality areas: Identify, Protect, Detect, Respond, and Recover. Aiming to improve overall CS aspects [22].

B. Vulnerability assessments

Vulnerability assessment of a CPS aims to identify security weaknesses and quantify their impact. Providing knowledge of exactly what should be secure, and why, before specific solutions are selected. The CS market has plenty of tools offering solutions for CS issues, developed by research labs, governmental institutions or by private CS companies. OCTAVE [23], [24] is one of well known approach, aiming to align CS activities with the goals and targets of the organization. Moreover NIST CS Framework was developed to assist industries with securing their infrastructure, to be more resilient to cyber attacks [25]. NIST framework provides guidance on how to improve CS for existing manufacturing systems. In recent work, NIST framework has been utilized as a SME CS evaluation tool (CET). Framework provides a 35-question online survey for IT-management to self-evaluate company CS maturity within the five NIST framework categories: identify, protect, detect, respond, and recover [10].

IV. Use case demonstrations

As set out by the Digital Europe Programme, Digital Innovation Hubs (DIH) will have an important role to stimulate the uptake of Artificial Intelligence (AI), High Performance Computing (HPC) and CS, for industry and public sector organisations in Europe. TRINITY[1] is one such DIH and has developed a wide set of demonstrators that aim to provide SMEs methods and tools to achieve agile production. Following, these demonstrators are presented and analysed with respect to CS. And if found vulnerable, several CS measures are recommended to be taken.

A. TRINITY core demonstration

Table I lists 18 demonstrators in different areas of robotics and industrial IoT, which were identified as the most promising to advance agile production, but has not yet been widely applied in industrial applications [26]. The specific technologies used in each demonstrator are high-lighted by keywords and, additionally, the technology readiness level (TRL) is presented.

Sixteen out of eighteen Trinity demonstrators focus on robotic functionalities or on systems that support robot programming or interaction. Only two demonstrators do not include robotics, and are focused on IoT. Only one of IoT demonstrators has CS as core functionality. In addition, the technological maturity of the demonstrators has an influence on their CS as well. That is, for technology validated in a lab (TRL4), validated in an industrially relevant environment (TRL5) or demonstrated in an industrially relevant environment (TRL6), the main focus is on functionality and not on the safe integration in operational environments.

B. CS analysis

Table II lists seven CS questions that quickly assess the state of the demonstrators with respect to CS. The questions can be broadly summarized to address three key issues:

KI-1: Cyber secure design - Prior to the design and development of the demonstrator, CS issues were identified and taken into account (Q1, Q3)

KI-2: Cyber security analysis - CS issues were taken into account and documented after development (Q2, Q3)

KI-3: System vulnerability - The technology utilized in the demonstrator can directly explain CS issues (Q4-Q7)

Key issues KI-1 and KI-2 address the greatest concern in current robotics (research) development. With functionality of the technology as main importance, integration typically takes a secondary role, and CS issues are not taken into account during the design stages. This can be clearly identified from the demonstrators as none of the use cases have performed CS analysis to identify potential risks and vulnerability threats during design or prior to the development. In addition, a relatively low number of demonstrators have taken into account and documented CS issues (4 demonstrators, or 24%), and only half of the demonstrators include awareness of CS concerns (9 demonstrators, or 53%).

The final key issue, KI-3, in CS for agile production addressed the particular technology utilized, providing an indication to the state of CS of the demonstrator. Control and operation of the robotic system is divided in three categories, vendor specific controllers (Q4), Programmable Logic Controllers (PLC, Q5) and other industrial communication or middleware systems (Q6). This provides insight into the system architecture and how the data flows. This can also show the vulnerabilities, as in the case of middleware (e.g. ROS1), CS issues are typically not taken into account. The OPC UA standard (IEC 62541) [28] is often used as a middleware to connect industrial equipment together, which has some security features embedded, however, there are still CS flaws/issues in the standard [29].

Vendor specific controllers (7 demonstrators, or 35%) are usually designed with some CS measures. The challenge of these controllers is keeping them up to date and getting updates from the vendors. Keeping vendor specific controllers up to date can be challenging since an industrial robot controller's lifetime is often longer than a standard industrial control system. Unfortunately, this means that some controllers have unpatched vulnerabilities that will never get updated, which is a significant CS risk. In some manufacturing systems having the industrial robot operational all the time is crucial. Therefore, some customers of controllers may postpone updates to the controller [30].

Programmable logic controllers (PLC) are, in simple terms, digital computers for automating an industrial control system [31]. In some systems they are used to control robots or a part of the robotic system. PLCs are placed between the field devices and the human-machine interfaces (HMIs), sending commands and receiving data. PLCs are programmable and can therefore be compromised, by a malicious control program loaded on the controller. It has also been shown that intercepting the communication of a PLC can be compromised with simple python scripts and open-source tolls [32]. However, only 2 demonstrators (12%) use a PLC for control of the system.

Another CS question addresses whether the demonstrator has a web interface, or can be accessed via other means (e.g. intranet, mobile, or cloud). The number of demonstrators that provide this is relatively low (6 demonstrators, or 35%). This might seem good since disconnecting a system from the network limits CS risks. However, a typical cyber physical production system has communication technology, intelligent network and data transmission features [33]. Using intranet, mobile, or the cloud in a manufacturing system could provide more flexibility and agility. Therefore, these systems will eventually need to be updated and connected to a network. This level of connectivity will mandate applying the CS measures regarding a system including a web interface or

TABLE I: Agile production use cases from [27]. Keywords: **HRC** - Human-robot collaboration, **AR** - Augmented reality, **VR** - Virtual reality, **CR** - Collaborative robot, **IR** - Industrial robot, **MR** - Mobile robot, **DT** - Digital twin, **OS** - Operator safety, **IoT** - Internet of Things, **S** - Simulation, **RP** - Robot programming, **CS** - Cyber security. A detailed description of all use cases can be found on `https://trinityrobotics.eu/catalogue/`.

Demonstrators		**Keywords**	**TRL**
1	Collaborative assembly with vision-based safety system	CR, HRC, OS, AR	6
2	Collaborative disassembly with augmented reality interaction	IR, HRC, OS, AR	6
3	Collaborative robotics in large scale assembly, material handling and processing	IR, CR, OS	6
4	Integrating digital context to a digital twin with AR/VR for robotized production	IR, VR, AR, DT	6
5	Wire arc additive manufacturing with industrial robots	IR, IoT	6
6	Production flow simulation/supervision	S, IoT, DT, VR, RP	6
7	Robot workcell reconfiguration	CR, RP, DT	6
8	Efficient programming of robot tasks by human demonstration	CR, HRC, RP	6
9	Dynamic task planning & work re-organization	MR, HRC, RP	5-6
10	HRI framework for operator support in human robot collaborative operations	IR, HRC, AR, OS	5-6
11	Robotized serving of automated warehouse	MR, RP	5
12	User-friendly human-robot collaborative tasks programming	CR, HRC, RP	5
13	Deployment of mobile robots in collaborative work cell for assembly of product variants	CR, MR, RP	5
14	Virtualization of a robot cell with a real controller	S, DT, RP	6
15	IIoT Robustness Simulation	IoT, S, CS	4
16	Flexible automation for agile production	IR, RP	4
17	AI-based stereo vision system for object detection, recognition, classification and pick-up by a robotic arm	CR, RP	4
18	Rapid development, testing and validation of large scale wireless sensor networks for production environment	IoT	4

TABLE II: High-level analysis of the demonstrators to assess and raise awareness of CS. Abbreviations: **DDS** - Data Distribution Service, **OPC** - Open Platform Communications, **OPC-UA** - OPC Unified Architecture.

Cyber security questions		**Applicable use cases**	**Total nr of use cases**	**%**
Q1	A CS analysis defining potential risks and vulnerability threats has been done and documented during design or prior to the development of the use case	none	0	0
Q2	CS concerns have been taken into account and have been documented	3, 4, 14, 15	4	24
Q3	Robotic system developers and engineers are aware of CS concerns in the use case	3, 4, 6, 7, 11-14, 17	9	53
Q4	Robotic systems are designed and operated only by vendor specific controllers	1, 2, 10, 11, 16, 13, 14	7	35
Q5	Robotic systems have been programmed, created and operated by PLCs	10, 14	2	12
Q6	Robotic systems have been programmed and/or are controlled and operated by ROS (1-2), DDS, OPC, OPC-UA, or other available interfaces	1-4, 6, 7, 9, 12, 13, 17	10	59
Q7	Robotic systems have a web interface, can be accessed via intranet, mobiles, internet or can be operated via the cloud	6, 7, 8, 11, 12, 14	6	35

accessed via other mediums.

C. CS measures

Awareness of CS issues have been raised to each individual demonstrator, based on the answers of the CS questions and its analysis. Different measures to harden the systems are then given, as listed in Table III. These are detailed as follows.

Isolation/segmentation or taking the robotic system offline is essential according to many standards, especially SANS [21]. 11 of the demonstrators have either segmented their network or taken it offline. In the case of the demonstrators that have not considered the measurements the components with the different functionality should be segmented from each other. In the case of demonstrator 5 and 6 which is heavily IoT dependent the industrial zone and manufacturing zone should be segmented.

There is only one demonstrator that has considered measurements for white listing of a robotic system. Whitelisting limits the access to the robotic system through limiting work stations and ports at the network level.

Access controlling can be achieved with a AAA-server (authentication, authorization, and accounting) [34]. There are many alternatives for such security capability, but for SMEs open-source choices could better suit the need. Almost all demonstrators have introduced these measures (15 demonstrators or 88%), thereby improving the system's CS and limiting the access to the system.

Vulnerability assessment provides a better prospective of the systems. The business owners can easily identify the existing weaknesses of the system. For two demonstrators (demonstrator 3 and 4), a vulnerability assessment of the robotic system has taken place and all vulnerabilities have been reported and are being handled (M4). The vulnerability assessment can be preformed with open source software such ass NESSUS [35].

CS is not an "add-on" to the network and security should be considered when designing and building a robotics system. The inclusion of security by design principles (M5) has not been taking into account by any demonstrator. The demonstrators are developed by research organisations or universities focusing mainly on robotics, therefore CS has not been considered when designing and building the system and it is an afterthought. Because of this, implementing CS would require major efforts to the re-design and re-implementation of the developed technology. Each of the

TABLE III: Measures to address the CS issues.

Cyber security measures taken		Applicable use cases	Total nr of use cases	%
M1	Isolation: the robotic system has been taken offline, or has been implemented on a segregated network	1, 3, 4, 7, 10-14, 16, 17	11	65
M2	White listing: the robotic system has been integrated in the network, but can only be accessed by a specific set of network operations and other machines	14	1	6
M3	Access, identity & authentication management: access to the robotic system (development and operation) has been limited to a specific set of users/applications, granted upon authentication	1-4, 6-14, 16, 17	15	88
M4	A vulnerability assessment of the robotic system has taken place and all vulnerabilities have been reported and are being handled	3, 4	2	12
M5	The application logic of the robotic system has been developed on the basis of security by design principles, taking into account application security	none	0	0
M6	Security capabilities offered by ROS2 have been considered or have been implemented in the robotic system	3, 4, 7, 12, 17	5	29
M7	Awareness of cyber security issues have been raised, but no serious preventative measures have been taken yet	3, 4, 6, 9-11, 13-15, 17	10	59

demonstrators should re-design the robotic system based on their use case and CS needs. The NIST framework [22] can be applied as approach for such purpose.

ROS2 as middleware has improved CS vulnerabilities, as compared to ROS1, by incorporating authentication, encryption and public key infrastructure. In addition, ROS2 is built upon the Data Distribution Service (DDS) standard. Demonstrators built with ROS1 could therefore migrate to ROS2, or at least consider to do so. This was done by 5 demonstrators or 29%.

A lot of businesses don't take security seriously before any incident. Most of the demonstrators (10 demonstrators, or 59%) are aware of CS issues for the systems, but have not taken any action regarding these issues. This excludes measures such as isolation and basic access control, since these are only minor fixes and do not resolve the CS issues that have been raised. Having awareness of CS issues can prevent further problems.

V. CS recommendations for SMEs

The most important CS recommendation for SMEs is to increase their level on CS awareness. Second step should be vulnerability assessment in order to find out existing CS vulnerabilities. Dedicated efforts should then be set to address and tackle current CS issues, and to monitor potential CS issues continuously. As CS may not be part of their core expertise, SMEs should follow these recommendations:

Support - Initiatives to get SMEs cyber secure are plentiful, and actions on (inter)national level should be taken [36].

Education and training - All personnel should be aware of CS issues and receive continuous training on identifying CS risks.

Continuous assessment - Vulnerability assessment should be carried out at regular intervals and documented and reviewed.

In order to secure a system, a number of standards and guidelines such as NIST 800-82 [1] and NIST Framework [22] are available. Following guidelines provided SMEs can implement their systems on a secure base or harden security of their existing systems. It should be noted that standards provide only guidelines and principles for CS, details and implementation is the responsibility of the implementer.

A number of security architectures as foundation for a system has been offered by distinct materials, such as SANS [21]. An architecture provides a base for the functionalities that SMEs implement. Therefore, it is vital to consider a secure architecture for any SME as primary steps. Architectures define computer networking concepts and security implementations such as firewalls and intrusion detection systems. Mentioned implementations are offered as commercial and open source products. Commercial products are often easy for SMEs to utilize but initial cost is out of range. Open source products on the other hand offer a free solution but might require expertise to setup.

CS is a continuous effort and has to be taken seriously, in order to not comprise a SMEs personnel safety, business and environment.

VI. Discussion

The current outlook for novel research and developments in agile production is promising. Multiple standards and protocols exist and can be followed and used as guideline for CS development. Initiatives that support CS are plentiful and national or European wide programs are available for financial (e.g., DIHs) and legislative support [36]. On a practical level, native support for CS and cloud-native applications are becoming the standard as well. This can be identified from product offering of commercial products such as PLCs with native cloud support and open source architectures such as ROS2 with CS as core feature.

However, CS issues can still be found while existing production systems are developed towards Industry 4.0 (e.g., cloud connectivity). For SMEs, the efforts and resources needed for the transitioning can not always easily be found or the skills required need to be obtained elsewhere.

The analyzed demonstrators represent a current offering of the TRINITY use cases and modules for SMEs to adopt, to achieve more agile production. In an ideal situation, CS would have been considered at the design phase of the TRINITY use cases and modules. Unfortunately in almost half of the demonstrators, CS has not been addressed sufficiently and efforts towards hardening require at least partial redesign of the implementation. The reason for this is that most works are a direct output from research that has only focused on the functional aspects of the demonstrator. However, as this project continues, emphasis is being put on CS and the migration to secure solutions.

VII. Conclusions

CS issues in manufacturing environments can threaten factory operations, lead to data theft and even harm CPS. Especially SMEs are at risk due to a potential lack of resources and knowledge to take dedicated CS measures. In this work we have addressed the state of CS in agile production and have analyzed 18 use case demonstrations, representing technologies and applications towards Industry 4.0. The analysis is done via two tables, one evaluating the functionality of the demonstrators and the other assessing the taken CS measures. An initial CS assessment revealed weak awareness of CS issues within the demonstrators, mainly because the functionality of the systems takes priority over CS. Several measures are presented to harden and secure the demonstrators towards outside attacks. Finally, the most important measure for SMEs to take is to increase awareness of CS related issues, as it is key to SMEs CS hardening.

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PUBLICATION IV

Common Educational Teleoperation Platform for Robotics Utilizing Digital Twins

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Common Educational Teleoperation Platform for Robotics Utilizing Digital Twins

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Abstract: The erratic modern world introduces challenges to all sectors of societies and potentially introduces additional inequality. One possibility to decrease the educational inequality is to provide remote access to facilities that enable learning and training. A similar approach of remote resource usage can be utilized in resource-poor situations where the required equipment is available at other premises. The concept of Industry 5.0 (i5.0) focuses on a human-centric approach, enabling technologies to concentrate on human–machine interaction and emphasizing the importance of societal values. This paper introduces a novel robotics teleoperation platform supported by the i5.0. The platform reduces inequality and allows usage and learning of robotics remotely independently of time and location. The platform is based on digital twins with bi-directional data transmission between the physical and digital counterparts. The proposed system allows teleoperation, remote programming, and near real-time monitoring of controlled robots, robot time scheduling, and social interaction between users. The system design and implementation are described in detail, followed by experimental results.

Keywords: digital twin; teleoperation; robotics; MQTT

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1. Introduction

Current challenges brought by ongoing conflicts, worldwide threats, and unequal economical conditions [1,2] are introducing major challenges to all sectors of societies. As a concrete example, pandemic restrictions have set limitations for student group sessions at university laboratories, forcing educational institutes to rethink practical arrangements of laboratory exercises [3–5]. Climate change requires an increased appreciation of environmental awareness and preferring green choices [1]. An example of a greener choice is the reduction of traveling to only situations truly necessary and favoring alternative approaches whenever possible. In addition to reduced traveling, changes in consumption habits are required; purchasing of new products should not be preferred, instead leasing or renting of existing equipment should be. Efficient utilization of existing equipment located in remote locations preserves the resources required for manufacturing new units. Equality can be promoted by offering people in developing countries the possibility of training remotely utilizing modern equipment [6,7]. As Bryndin [8] notes, the aim of Society 5.0 is to create equal possibilities for all individuals and to create an environment for realizing equal possibilities. A possibility to participate from distant locations would provide a solution to overcome pandemic restrictions, enable exercising without traveling, and increase the utilization rate of existing equipment, supporting a human-centric approach of utilizing i5.0 technologies. In this paper, a common teleoperation platform for robotics utilizing digital twins(DT) is presented as a solution for the distant utilization of robotics.

Moniruzzaman et al. [9] defined robotic teleoperation as a robot that is controlled or managed by a human operator over a data connection. Bi-directional communication between the robot and human operator allows the human operator to provide orders and suggestions to the tasks while the robot executes the tasks based on the input from the human operator. In the scope of this proposal, bi-directional communication enables a user to control robots at the university laboratory from any location, therefore saving time and environmental resources consumed on traveling. Teleoperation platform services are also available for students abroad and studying at other universities. There are previous studies on using teleoperations in universities. Marin et al. [10] proposed a telerobotic system, allowing students and scientists to control robots remotely. In addition to this work, the solution presented here provides time resource management to enable the scheduling of teleoperated equipment and Cybersecurity considerations. A trivial calendar application is provided as a front-end for time resource management, allowing students to reserve time resources for a specific robot to exercise robotic skills. In this proposal, the scope of resource management is limited to students reserving time slots to study robotics. The scope can be broadened to include equipment sharing and rental between companies and educational institutes.

Sharing time resources of available equipment requires user authentication and authorization to create a link between time resources, equipment, and user. The platform presented includes methods for user registration, authentication, and authorization. Daily tasks for user registration, strong password creation, and password recovery have been automated to save administrator time.

Social communication is an important feature for students participating in education from distant locations [11,12]. Communication is needed by students to request help for the usage of the platform and to exchange experiences with fellow students, lecturers, and IT support. On the platform presented, social communication is offered in the form of a live chat, a discussion forum, and an online video meeting. Digital twin (DT) was chosen as a key approach for implementing teleoperation. DT is a digital presentation of a physical world object, serving as a bridge between the physical and cyber world [13]. DTs enable monitoring and operation of physical equipment, production lines, factories, and smart cities independent of location. In this context, DTs enable students to perform practical exercises by teleoperating robots physically located in a university laboratory. The platform includes DTs of mobile, industrial, collaborative, and scara robots for teleoperation. Bi-directional open communication standards are utilized to link digital and physical twins. The digital presentation features a dashboard for controlling and monitoring physical twins. To provide a near real-time view for the teleoperation, a video stream of a physical environment is embedded in the digital presentation.

The platform proposed in this paper is accessible and cybersecure (CS). CS has been considered a key enabler for a sustainable platform performing data transfer and providing services over the internet. CS is also a building block of physical safety when Cyber-Physical Systems (CPS) such as teleoperated robots are considered [14,15]. Weak CS can enable an attacker to gain control of physical equipment and cause physical damage to equipment and the surrounding environment [14]. CS of the proposed platform is implemented by the following methods: secure authentication, authorization, firewall rules, and data encryption. The best efforts by the authors have been made to protect data connections and services of the proposed platform against cyber attacks. Addressing CS, however, is continuous work, requiring periodic reviewing and actions such as vulnerability scans and updates of vulnerable services. Previous studies on utilizing teleoperation for robotic laboratory exercises lack consideration of CS. Instead of writing a single paragraph about CS, in this paper, CS aspects are considered in each of the following chapters.

While many approaches of educational robotics platforms have been reported previously, implementations presented have been fragmented with restrictions or absence of at least one of the following features: social communication, resource sharing, content management, teleoperation, or support for mobile devices. The proposed approach contains the aforementioned services and is based on open-source software. Figure 1 presents the platform requirements and services. Research questions to answer are: Is teleoperation platform utilizing DT's suitable for robotics education and training? Is common teleoperation platform implemented with open-source software cybersecure?

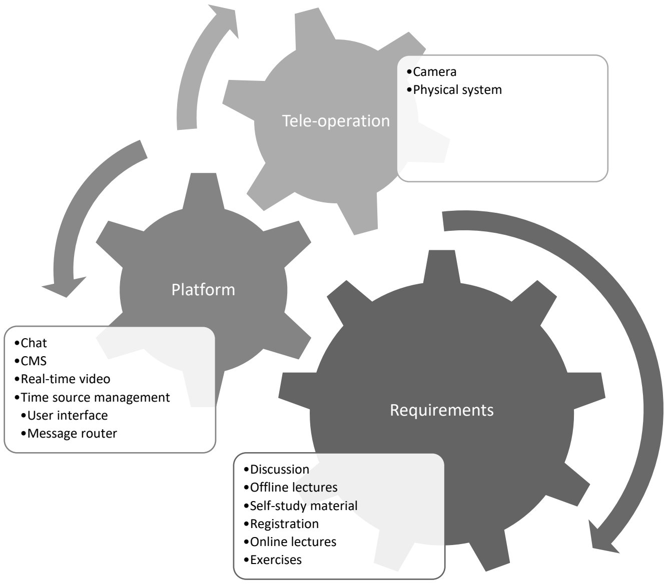

Figure 1. Figure describing user requirements and services providing required functionalities. Figure also describes connections between platform services.

The contributions of this work are as follows:

1. Implementation of robot teleoperation platform utilizing DT's
2. Method for time-resource management of teleoperated equipment
3. Cybersecurity road-map for teleoperation platform
4. Teleoperation platform based on open-source software

The remainder of the paper is organized as follows: Section 2 provides methods and approaches, including functional and non-functional requirement specifications of the platform. Section 3 presents a literature review describing existing solutions and previous research on the topic. In Section 4, implementation and validation of platform is presented and further discussed in Section 5. Section 6 concludes this paper.

2. Methods and Approach

Methods utilized during the development of the proposed platform are presented here. Requirement specification and requirement validation presented in Section 2.1 is considered a fundamental guideline during the implementation phase described in Section 4. The development phase begins with platform architecture specification and validation. Development is followed by implementation, including iterative programming, testing, and functionality validation tasks. To validate the functionality of teleoperation and digital twin data transfer, one high-level task was defined for each robot. Tasks were chosen based on the capabilities of the robot type in a question and are explained in Section 4.6. After implementation conforms to defined requirement specification, the platform was considered ready for evaluation in real applications. Figure 2 presents the methodology of this work to plan, develop, implement, and validate the proposed platform. Methodology presentation is based on work of Garcia et al. [16].

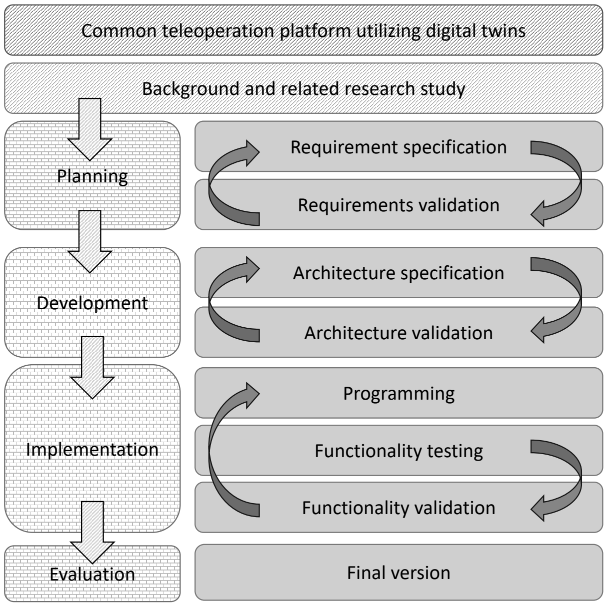

Figure 2. Methodology utilized in this work to develop and validate platform [16].

2.1. Requirement Specification

Requirement specification for the platform was defined based on needs for training basic skills in robotics and on requirements found during a related research study described in Section 3. Group defining requirements specification consisted of authors of this paper having pedagogical, software engineering, ICT, and robotic knowledge. Requirements were divided into two main groups: Functional (F) and Non-Functional (N). Functional requirements describe requirements directly related to the functionality of the platform such as teleoperation and monitoring of robots. Functional requirements were further divided into Must and Could, depending on the urgency to implement specific requirements on the platform. Some of the requirements listed are considered future work and are beyond scope of this publication, and the level for those requirements is defined as Could. Those requirements are considered in more detail in Section 5.

Non-Functional requirements define quality requirements, such as how many users should be supported or the availability of the platform. Non-Functional requirements were divided into sub-categories of Usability, Security, and Performance depending on the nature of the requirement. Requirements specified in Tables 1 and 2 are referred in Section 4 to indicate which requirement specific implementation task corresponds to.

Table 1. Functional requirements.

ID	Name	Description	Level
F1	Digital twins	The system can be used as a digital twin allowing bi-directional data transmission from simulation models to physical robots and vice versa.	Must
F2	Teleoperation and programming	A registered user can teleoperate and program available robots physically located in laboratories. Robot movements can be controlled directly through an user interface or using robot programs.	Must

Table 1. *Cont.*

ID	Name	Description	Level
F3	Monitor	The laboratory can be remotely monitored through the system. This is implemented using cameras that are streaming to the system.	Must
F4	Registration	A person can register to the system through a dedicated web-page using a valid email address. Person can create a password after receiving confirmation email.	Must
F5	Role definition	Users can have different roles: user, publisher, and admin. Roles can be modified through the system by admins.	Must
F6	Scheduling	Users can make reservations on available robots for teleoperation and programming through the booking calendar, including time-slot management.	Must
F7	Discussion	Users can discuss or request help about different topics on discussion forum or chat. Admins can delete any thread.	Could
F8	Download/upload	Digital material can be stored on, accessed in, and downloaded from the system by users. Material can be documents such as images, videos, audio, and text documents.	Could
F9	Examination	Exams at different scales can be performed in the system. Different scales mean that a student can execute the course only partially. Evaluation pass/fail.	Could
F10	Certificate	The system provides a participation certificate based on the examination. The certificate includes the scope on the course taken. The certificate is sent by e-mail.	Could
F11	XR support	XR-techonology can be used to visualise simulations, teaching, and remote usage.	Could
F12	Virtual deployment	Robots can be virtually deployed using the system.	Could
F13	Group formation	User groups can be formed by all user types and groups can collaborate on same tasks.	Could
F14	Group lecturing	Lecturer can arrange meetings with groups. Meetings can be used for lecturing, mentoring, steering, etc.	Could
F15	Progress tracking	The system tracks users on which parts of course they have completed/studied.	Could

Table 2. Non-functional requirements.

ID	Description	Category
N1	The systems clearly focuses on robotics.	Usability
N2	Suitable for beginners and professionals, independent of the entry level. Programming experience or prior knowledge of robotics is not required.	Usability
N3	CS is taken into account. Remote users cannot access the system further than predefined robots. Additionally, robot functionality is restricted for safe operations.	Security
N4	Safety taken into consideration in remote usage.	Reliability

Table 2. *Cont.*

ID	Description	Category
N5	Comparison of live and captured lectures. Feedback from students.	Usability
N6	Support for platform usage.	Usability
N7	Support for different languages (lectures, user interface).	Usability
N8	Laboratory exercises can be done independently from the previous progress. Any exercise can be chosen.	Usability
N9	20 simultaneous users.	Performance
N10	Possibility to transfer material from other platforms.	Usability
N11	Lectures can be online, offline, and live (F2F).	Usability
N12	Material will be organised in sections so that certain sections form ensembles.	Usability
N13	The system is available 24/7.	Reliability
N14	Email address used for registration is validated.	Usability
N15	Delay in stream when observing a physical robot should be less than 250 ms.	Performance
N16	Exercises can be in form of game. Either 3D featuring extended reality or 2D desktop mode.	Usability

3. Background and Related Research

The related research review aims to find software components required to build a common teleoperation platform for robotics utilizing digital twins. The chosen components meet the demands of the requirement specification in Section 2.1. An overview of recent research on DTs and teleoperation is performed with a focus on robotics and education. The modern data transmission protocols are reviewed, as DTs require a bi-directional data flow between the physical and digital twin. The latest research on real-time video transmission protocols for efficient teleoperation is reviewed to meet the requirement N15. In addition, authentication and authorization of an online system are essential for CS providing privacy and security to users requirements F4, F5, and N3.

3.1. Digital Twin

The concept of Digital Twin (DT) was presented in 2002 by Michael Grieves as a conceptual idea for Product Lifecycle Management [17]. Grieves presented virtual and real systems having a link throughout all phases of the product lifecycle from design to disposal. Since then the DT definition has been evolving, and misinterceptions of the “twin” metaphor have existed [18]. In this paper, definitions presented by Cimino and Kritzinger are considered as guideline definitions for DT. Cimino defines DT as a virtual copy of a physical system able to interact in a bi-directional way [19]. According to Kritzinger, bi-directional automated data flow distinguishes DT from the digital model and digital shadow [20]. DT has been utilized in the analysis, monitoring, maintenance, engineering, and testing [21]. DTs can be used to represent a single system such as a CNC machine, industrial robot, welding equipment, autonomous vehicle, or larger entities such as oil refinery or chemical plant [21]. DT enables a user to interact with low-level functions available on the physical part of the twin. A physical twin is an actual system put together to perform a certain function. Digital twin as a digital presentation of physical twin can present physical parameters such as temperatures, linear positions, and vibration frequencies in digital format. DT enables user interaction with the physical twin, providing operator teleoperation capabilities [22]. Teleoperation enables operators to control robots over large physical distances [22,23]. In the context of this paper, DTs enable control of physical robot cells, providing a method for teleoperation. Digital Twin consortium provides glossary [24] of DT-related terms. The following terms will be used in our paper later on and are explained here:

- Digital twin is a virtual presentation of real-world entities and processes, synchronized at specified frequency and fidelity
- Physical twin is a set of real-world entities and processes that correspond to a digital twin
- Digital twin platform is a set of integrated services, applications, and other digital twin subsystems that are designed to be used to implement digital twin systems
- Digital twin system is a system-of-systems that implements digital twin
- Cyber-Physical system is a system consisting of physical and digital systems integrated via networking.

DT concept is now in its third generation where AI and deep learning algorithms utilize online data [25,26]. First generation DTs were virtual presentations based on scripting languages and second generation of DTs introduced in 2012 were more simulation-oriented [25]. In addition to presenting individual systems, DTs are capable of combining individual DTs to present complete factories, supply chains, airports, and smart cities [21,25]. International Organization for Standardization (ISO) has defined standards for the DT framework in 2021 [27], and standardization is an indication of DT as a mature concept. Deep-learning can enable DTs to self-optimize and thus advance autonomously [25,26].

A cyber attack against a DT may enable an attacker to gain access to physical twin [14]. Therefore, unauthorized modification or destruction of data can lead to unexpected behavior of physical twin, leading to catastrophic damages [14,28]. According to Holmes et al. [28], the amount of CS attacks against DTs are increasing. Integrity and confidentiality of data transfer between physical and digital twins are identified as the main CS challenge for DTs [28], as CS attacks disrupting the integrity or confidentiality of data might endanger the safety of the physical twin environment.

Data Flow between Physical and Digital Twin

DT definition requires automated bi-directional data flow between physical and digital parts [20]. Synchronized data transfer from individual sensors to digital presentation and from digital presentation to individual actuators is a key enabler of DT concept [19]. This enables users to monitor and control physical twin by a user interface of a digital twin. Furthermore, the data flow of individual DTs can be combined to represent complete factories or complete supply chains [25]. Connecting individual DTs to present larger entities, a common platform is required. A common platform utilizing open connection standards enables flexible combining of DTs. Currently, OPC Unified Architecture (OPC UA) is a widely adopted open standard cross-platform solution for data exchange [29]. OPC UA client-server model has lately been accompanied by publisher–subscriber solutions developed for IoT such as Message Queue Telemetry Transport (MQTT).

MQTT, originally developed by Andy Standford-Clark and Arlen Nipper [30], is considered one of the most popular messaging protocols for IoT- and IIoT-devices [31]. MQTT has been widely adopted in logistics, automotive, manufacturing, and smart home applications. MQTT protocol has three participants: publisher, subscriber, and broker. A publisher is a device publishing certain topics such as temperature and humidity. A subscriber is a device subscribing to certain topics to receive information. Both are connected to a broker to deliver published topics to subscribers [31].

MQTT was not originally designed with CS in mind. Current MQTT-versions 3.1.1 and 5 offer authentication as a measure against CS attacks. To encrypt MQTT messaging Transport Layer Security (TLS) is needed and is supported by some MQTT-implementations [31]. Authentication and encryption provide strong protection against CS attacks. MQTT meets requirements F1, F2, and N3 of digital twins, teleoperation, and CS.

OPC Unified Architecture is a cross-platform open standard IEC62541 for data exchange. The standard is actively developed by independent committee OPC Foundation [32]. The history of OPC (OLE For Process Control) began when Microsoft introduced the BackOffice suite of server products in 1996 [33]. OPC UA standard defined in 2006 is widely recognized in industrial automation and has been chosen as Industry 4.0 reference standard [29,34]. In 2018, part 14 was added to define publisher/subscriber communication model in addition to client/server model [35]. MQTT, AMQP, and UADP messaging protocols are currently supported to offer publisher/subscriber communications to OPC UA.

OPC UA standard is secure-by-design, providing confidentiality and integrity by signing and encrypting messages [14]. Basic security provided by username and password authentication can be extended with encryption to enable a high level of CS.

3.2. Teleoperation

Teleoperation of robots has been studied for decades since the beginning of robotic systems in the 1950s [36]. MIT started to study teleoperation in the mid-1960s and the mid-1990s when prof. Sheridan reported progress in the field of teleoperation in several countries and application areas including space, undersea, mines, toxic waste cleanup, telediagnosis, and telesurgery [37,38]. Since then, teleoperation applications have been researched for healthcare [23,39,40], industrial [41], education [5,10], underwater [42], nuclear [43], and energy applications [44]. González et al. [41] proposed a teleoperation system to control industrial robots. The system proposed allows the operator to perform finishing, sanding, deburring, and grinding operations, which are hard to do with industrial robots. By using teleoperation it is possible to preserve the physical integrity of human work and to allow people with motor disabilities to perform grinding and sanding processes. A teleoperated robotic system for healthcare performing ultrasound scanning was presented by Duan et al. [39]. Tests were conducted and proven that using teleoperated robots to take ultrasound was safe and effective [39]. Caiza et al. [44] used the lightweight protocol MQTT for the teleoperation of robots. An operator can be in a different location and control the robot movements and actions remotely. In the application proposed by Caiza et al., an operator can control a mobile manipulator to perform inspections on oil and gas equipment [44].

Real-Time Video

Low latency of real-time video transmission is critical in teleoperation applications [45]. Delay in video transmission has a negative impact on user experience and may cause the user to misguide teleoperated equipment. Web Real-Time communication project (WebRTC) is an open-source project offering near real-time web-based communication [46]. Most modern web browsers support WebRTC, and Round Trip Times of 80 to 100 milliseconds have been measured on mobile platforms [47]. WebRTC utilizes User Datagram Protocol (UDP) for video streaming. Since UDP does not support congestion control, a custom congestion control algorithm is required to control the video stream.

3.3. Authentication and Authorization

To meet requirements F4, F5, and F6, tools to authorize platform users and define user permissions are needed. Most modern CMSs' provide described functionality and also tools for website content management [48]. CMS provides schemes and front-end for user registration, strong password creation, password authentication, and password recovery. Currently, three major open-source CMS solutions are WordPress, Joomla, and Drupal [49]. A wide variety of third-party plug-ins are available for mentioned three major CMS. Plug-ins can add features such as calendars, clocks, and photo galleries to CMS [48].

To allow registered users to log in to all services on the platform with a single username and password, a single sign-on (SSO) method is required. Single sign-on allows registered users to log in once and access all services on the platform. Open Authorization 2.0 (OAuth 2.0) is a token-based open standard for authentication and authorization [50]. OAuth 2.0 is a widely utilized standard in Internet communications utilized by Google, Amazon, and Paypal [51]. Traditional server–client style authentication is based on sharing credentials between resource owner and client. Sharing credentials with clients can lead to password leaks, data breaches, and unwanted access to protected resources [50]. OAuth 2.0

differs from traditional server–client style authentication by passing access tokens instead of credentials from the authentication server to the client. OAuth 2.0 enables users to utilize all services on the platform by creating single credentials on Drupal CMS. OAuth 2.0 is directly related to requirement N3.

4. Implementation and Validation

4.1. System Architecture

The system architecture of the platform was defined based on requirement specification and software component selections described in Section 3. Internal and external connections of architecture are described in detail in Figure 3.

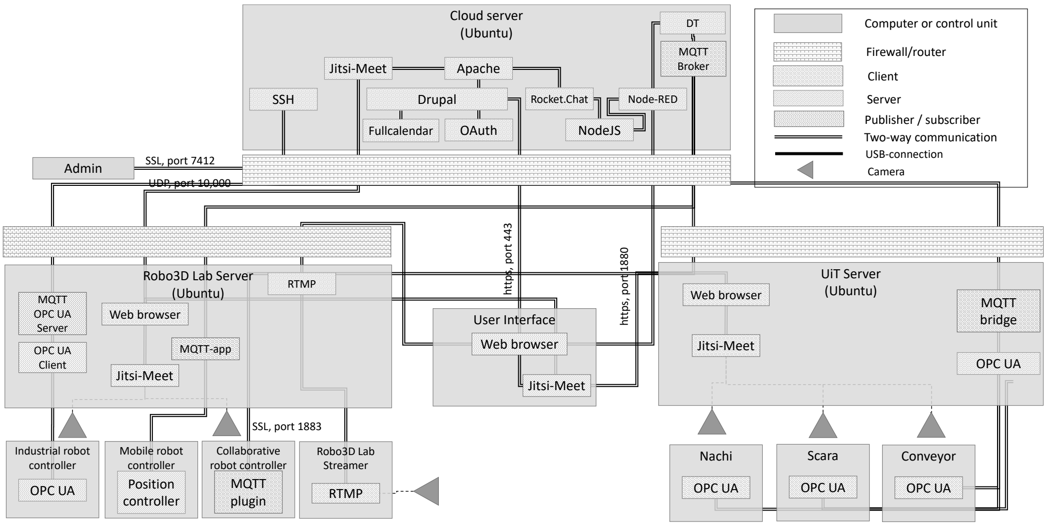

Figure 3. Platform internal and external connections.

The main part of platform system architecture is cloud server running services required to enable the platform for digital twins. Jitsi-Meet, Node-RED, and Mosquitto-MQTT services are directly related to the teleoperation of robots. DTs on the platform are digital entities validating and passing data between teleoperation user interface and physical systems. DT implementation of the platform is described in detail in Section 4.5. NodeJS runtime is required to run Node-RED, DTs, and Rocket.Chat servers on the system. Apache is required to host Drupal CMS and to act as a secure reverse proxy for Rocket.Chat and Jitsi-Meet services. In addition to content management, Drupal and OAuth-plugin provide registration, authentication, and authorization of users. Fullcalendar-module is required to enable functionality for time-resource management. SSH–server provides administrator access to the cloud server.

Robo3D Lab Server is located at Centria robotics lab. The purpose of this server is to act as a link between the cloud server and robots located at Robo3D Lab. Robotic systems available on the platform are physically connected to the Robo3D Lab server by LAN and WLAN connections. Additionally, web cameras utilized for monitoring teleoperated robots are connected to this server by USB connection. Robo3D Lab server is running OPC UA server and client to connect the industrial robot to cloud server, MQTT-app to connect mobile robot, and Jitsi-Meet client to stream video to Node-RED user interface. Additionally, the Kandao 360-camera streamer is connected to the Robo3D Lab server to stream a 360 view of the laboratory for a user to control and locate the mobile robot.

UiT Server is located at the UiT manufacturing laboratory in Narvik, providing a link between the cloud server and equipment located in Norway. Industrial and Scara robots and the conveyor system are connected physically to UiT Server utilizing LAN connections. Similar to the Robo3D Lab, server web cameras for monitoring CPS are connected to the server by USB connections. The server is running OPC UA Server and OPC UA/MQTT-bridge to connect robots to the cloud server.

4.2. Cloud Server

To set up our platform, DNS address was registered for the project at Centria's DNS server, redirecting all requests to the static IP address provided by the cloud service provider. Ubuntu 20.04 with the latest updates was installed to provide a server OS. Apache, PHP, and MySQL server stack were installed on top of Ubuntu and configured to host Drupal CMS, Rocket.Chat, Jitsi-Meet, and Node-RED. A firewall was enabled on both the Ubuntu server and cloud service, allowing access to only ports required for platform functionality explained in Figure 3. CA certificate request was approved by GEANT Vereniging, and after approval, Apache was set up to only accept encrypted HTTPS connections. These steps correspond to requirements N13 and N3, requiring a 24/7 system availability, and CS was taken into account by encryption described in Tables 1 and 2.

4.2.1. Content Management System

Drupal provides automation for user registration, secure password creation, password recovery, and permission management tasks. Drupal also features calendar and modern authorization server plugins and was therefore chosen as CMS for the platform. Drupal CMS was installed to provide a front-end of the platform and a secure mechanism for user registrations, password recovery, and authentication. The front end of the educational platform was created with content management tools provided by Drupal. The front-end consists of menus, web pages, articles, and document files. Providing platform users information about utilizing platform and robotics study materials, Drupal add-on "Open authentication 2.0"-server described in Section 3.3 provides trivial and secure login to platform services Rocket.Chat, Node-RED, and Jitsi-Meet. Drupal add-on module Fullcalendar-module provides a method for teleoperation time resource management. Drupal CMS and add-on modules described providing solutions for requirements F4, F5, F6, and N3, N6, N7, N12.

4.2.2. Time Resource Management

FullCalendar-module was installed as a time resource manager. The back-end of FullCalendar is written in PHP and the user interface in Javascript. Since FullCalender-module does not offer logic for user-specific time resource management, the module source code was modified to include user id information for events and to monitor current time and reservation time, including user id and monitoring of current time enabled implementation of logic needed for time resource management. FullCalendar-module is directly related to the scheduling requirement described in requirement F6.

4.2.3. Real-Time Video Server

Jitsi-Meet utilizes Google Congestion Control (GCC), which is the most widely utilized congestion control algorithm for WebRTC [47]. There is a variety of open-source video conferencing applications based on WebRTC, such as BigBlueButton, Jitsi-Meet, and OpenVidu [46].

Jitsi-Meet was chosen for the proposed platform since it has been proven to perform well compared to BigBlueButton and OpenVidu [46]. Jitsi-Meet is a collection of open-source projects providing voice, messaging, desktop sharing and video conferencing applications in real-time browser-to-browser fashion [47,52]. CS is built-in, as Jitsi-Meet accepts only encrypted communication. User authentication is also possible and authentication was set up for this implementation.

Jitsi-Meet server provides common features of videoconferencing for the platform. The most important feature is web-based real-time video streaming. Video meet provides near real-time monitoring of teleoperated robots and enables a way for students and teachers to communicate. Jitsi-Meet was installed on a cloud server utilizing a ready-made installer. Jitsi-Meet requires SSL encryption and encryption was set up with the CA certificate described earlier. Jitsi-Meet CS was further improved by allowing only OAuth 2.0 authenticated users to start and join meetings on the platform. Jitsi-Meet relates to requirements F2, F3, and N3, N8, N9, N11, and N15.

4.2.4. Teleoperation User Interface

Node-RED was chosen as a development tool for the platform teleoperation user interface. Node-RED is a flow-based programming tool developed by Nick O'Leary and Dave Conway-Jones at IBM [53]. Node-RED provides visualization of MQTT-topics by web-based flow-editor [53]. Flow-editor provides a library of useful functions and templates, integration of custom Javascript code blocks, and connections between code blocks. Node-RED requires NodeJS runtime and runs as a service on a cloud server or local workstation. Node-RED is well documented and the developer community is active. Node-RED offers encryption of data and authentication of users by username and password or OAuth2 token as CS measures.

Node-RED server setup allows connections by default on port 1880. Node-RED is an important part of the platform connecting with DTs, providing an interface to control and monitor CPS. After setting up, Node-RED flows and dashboards to control robots at Ylivieska were created. Node-RED provides native support for SSL encryption and encryption was set up by utilizing the CA certificate described earlier. Node-RED relates to requirements F1, F2, F3, N2, N3, N8.

4.2.5. Cloud Data Transfer

Mosquitto was chosen as MQTT-broker for the platform, as it provides authentication and SSL-encryption with CA certificate [54]. Mosquitto MQTT-broker was set up to route messages between digital and physical twins. Port 1883 was specified for non-encrypted data transfer and port 8883 for encrypted. Authentication and encryption of data was enabled and connections without authentication were disabled. Encrypted connections were secured with CA-certificate provided by GEANT Vereniging. Simple topic structure was defined for publishing and subscribing messages. nnnTopic/from was defined as topic for receiving messages from equipment and nnnTopic/to was defined as topic for sending messages to equipment. For example, fanucTopic/to and fanucTopic/to were defined as topics for Fanuc LR-mate industrial robot to publish and subscribe messages.

A combination of OPC UA and MQTT standards provide industry-standard data exchange between digital and physical twins. These two protocols were chosen for data exchange on the platform proposed. These protocols are widely supported by IoT and IIoT devices and are capable of cross-communication. Open62541 was chosen as the OPC UA implementation for this project since it has been proven CS and to use the least computational resources [14,29]. Open62541 corresponds to requirements F1 and N3.

4.2.6. Social Communication

Rocket.Chat was set up to provide a way of social communication for platform users, administrators, and developers. Users do not always require real-time communication and instead chat type communication is sometimes more convenient. Rocket.Chat is set up to require a valid Drupal user account, and to allow anonymous messaging. Anonymous messaging lowers the bar to raise questions related to exercises and usage of the platform. Rocket.Chat supports OAuth2.0 and a valid Drupal user account is verified from CMS. To enable encrypted secure connections for Rocket.Chat it was set up with Apache Reverse-Proxy, as described in Rocket.Chat manual [55]. Rocket.Chat relates to requirements N2, N6, N3, and F14.

4.2.7. Vulnerability Scans

After installation, vulnerability scans on the platform were performed with Nessus and OWASP ZAP software. The first scan revealed several CS risks on the platform. The server was not running the latest versions of Apache and PHP. After updating Apache, PHP, and disabling weak SSH–algorithms, only fine-tuning of Apache parameters to hide server version information was required. As the latest scan indicated no CS issues, the platform was considered currently up-to-date and cybersecure. However, since new security issues appear daily, vulnerability assessment is scheduled to run monthly. The report is e-mailed to the site manager and measures to correct CS issues will be taken. Periodic vulnerability scans are directly related to the requirement N3.

4.3. UiT Manufacturing Laboratory

At the manufacturing laboratory in Narvik, Norway, there is a reconfigurable manufacturing system (RMS) that consists of multiple platforms. The platforms can be easily moved to any location in the environment. Three of the platforms in the RMS have been connected to the cloud system; two robot platforms and one conveyor platform.

4.3.1. Industrial Robot

The Nachi robot is connected to a CFD-0000 controller and can be used with other PLC systems, but it does not allow for controlling from an external computer. Therefore, a FD High Speed (FD-HS) system is used, which is connected between the CPU board and servo board of the controller and allows for control by an external computer. The FD-HS system can only be used for joint control, and therefore, a small NUC computer is added with ROS and MoveIt for inverse-forward kinematics calculation. In addition, the NUC computer is also used to connect the robot with the OPC UA server for remote operation.

4.3.2. Scara Robot

The original controller of the Scara robot had become obsolete and has been replaced with a LinuxCNC controller, and a second control computer (NUC computer) is added to connect the robot with the OPC UA server. The second control computer also runs ROS and uses MoveIt for the inverse-forward kinematics calculation, the same as the Nachi robot.

4.3.3. Conveyor

The conveyor includes the motor controller and five distance sensors. Figure 4 shows the control interface of the conveyor platform. Users can control the conveyor velocity and direction while reading the sensor values in this interface.

Figure 4. Control interface of conveyor with embedded live video view.

A Raspberry Pi operates as the control computer to control the motor of the conveyor, collect data from the sensors, and synchronizes the motor and sensor data with the OPC UA server.

4.3.4. UiT Server

For the local system in Narvik, the OPC UA server is used to gather/upload data from the local platforms and distribute the data from the cloud to each of the robot arms and the conveyor. To communicate with the robot arms there are two sets of variables: requested joint values and current joint values. If the requested values in the OPC UA server are changed, the robot will automatically start to move towards the new requested values. The current value is updated while the robot is moving. An illustration of the connection can be found in Figure 3.

The cloud server uses MQTT for communication. Therefore, a communication program synchronizes the data between the local server in Narvik and the cloud server MQTT.

4.4. Centria Robo3D Lab

At Ylivieska Robo3D Lab, two articulated arm robots and one mobile robot were chosen as hardware for implementation. The industrial arm robot is Fanuc LR-Mate intended for educational purposes. Fanuc LR-Mate is an industry-standard robot, providing 6 rotary joints for positioning and a gripper for attaching and detaching work pieces. The collaborative arm robot is Universal Robot UR3. UR3 is a collaborative robot providing 6 rotary joints, an adaptive gripper, and functions enabling human–robot collaboration. In addition to robots, a server PC was required. Robo3D Lab server is required to Host OPC UA client/server for Fanuc robot, stream real-time video broadcast for a collaborative and industrial robot, and host custom Python script to control a mobile robot. Configuration and connections of Robo3D Lab server are described in Figure 3.

4.4.1. Industrial Robot

Fanuc industrial robot controller provides OPC UA server for communication, MQTT is not currently supported. Therefore, custom OPC UA to MQTT-bridge was implemented. After enabling the OPC UA server option, the OPC UA server with factory default structure was running on a robot controller. Default structure included current position registers and alarm registers. A requested position register was added to receive commanded joint positions from the platform user interface. OPC UA client and server are modified implementations of Open62541. OPC UA Client is a connector between the robot OPC UA server and Robo3D Lab OPC UA server. The purpose of the OPC UA server is to act as gateway routing messages received from implemented OPC UA client to the cloud server MQTT-broker.

Fanuc robot OPC UA server does not support authentication or encryption of OPC UA data connections. To maintain CS confidentiality and integrity of data transfers between robot and platform, an isolated subnet connection consisting of only Fanuc LR-Mate robot and Open62541 implementation was set up. Server running Open62541 implementation utilizes two network adapters: one for connecting to an isolated network, including the Fanuc robot, and one for connecting to the internet router. Connections of setup are described in Figure 3.

Physical safety considerations for this robot are fully considered by the manufacturer, as this robot cell is CE-approved. The robot is installed inside a fully enclosed structure accessible only through a sliding door. The sliding door is secured by a safety switch stopping robot motion if opened.

4.4.2. Collaborative Robot

Universal Robot UR3 controller does not provide OPC UA or MQTT communications by default. Instead, the controller provides the possibility to install third-party applications, including OPC UA clients and MQTT connectors. In this case, MQTT-connector provided by 4Each software solutions was installed on the robot controller. 4Each MQTT Connector enables publishing and subscribing messages to MQTT-broker.

MQTT-connector connects to the cloud server transmits robot's current position and receives the requested position from the user interface. The program was also modified to allow commanding the robot to Tool Centre Point (TCP) to requested XYZ-coordinate positions.

The user interface created with Node-RED consists of six gauge-type indicators for current joint positions and sliders for each joint to set the wanted position. Above the gauge and slider elements is an embedded live video of a collaborative robot station. The user interface is presented in Figure 5.

Figure 5. Control interface of collaborative robot with embedded live video.

A risk assessment was conducted for this robot to evaluate possible safety risks regarding teleoperation. UR3 robot differs from Fanuc industrial robot described previously since it was not delivered as a complete cell but as a robot arm and controller unit. The final installation of the robot, gripper, and controller was conducted by Centria, and no CE approval for a complete cell was provided. Risks during teleoperation of the robot are that people near the physical robot are not aware of teleoperation. UR3 is a collaborative robot, designed to share working space with humans so the risk for physical harm is small. Enclosure manufacture of transparent polycarbonate sheet could provide added protection if required.

4.4.3. Mobile Robot

Omron LD-250 was chosen as a mobile robot for the platform. LD-250 provides Wifi-connection and proprietary command-line interface "ARC link" to control robot movements and to request the status of the mobile robot online. The mobile robot was connected to the ASUS router described earlier, and a Python-based MQTT application was written to send commands to the robot and request status information from the robot controller. MQTT-app is running on Robo3D Lab server and connects to MQTT-broker with paho-mqtt client. The control interface for the mobile robot was implemented on top of the floorplan image of Robo3D Lab. On the higher layer on top of the floorplan, clickable circle objects were created. A user can send pre-defined locations to the mobile robot controller by simply clicking circle objects on the floorplan. Real-time video of mobile robot movement is provided by Kandao 360 camera installed stationary in Robo3D Lab. Video is streamed from Kandao 360 camera to the Robo3D Lab server utilizing RTMP protocol. Figure 6 presents mobile robot user interface.

Physical safety considerations for this robot are fully considered by the manufacturer as LD-250 mobile robot is CE-approved. Mobile robot has sensors to detect and avoid obstacles in a planned path.

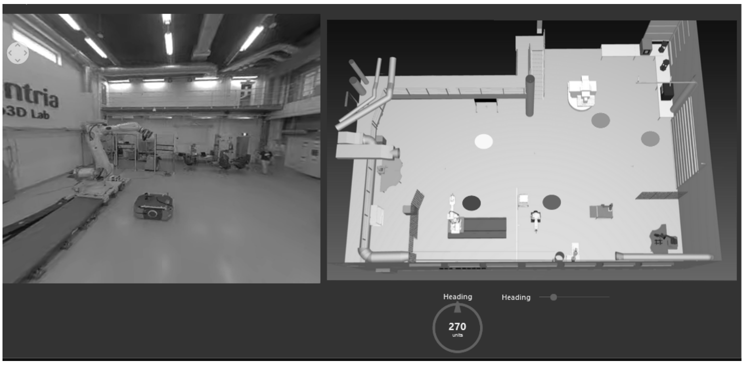

Figure 6. Control interface of mobile robot with embedded live video view.

4.5. Digital Twinning

As already mentioned, DTs are core components of the platform presented. Each physical system connected to the platform has a digital twin counterpart and automated data flow between physical and digital twins. DTs on the platform are implemented to present physical parameters of CPS, such as current joint and coordinate positions. In addition to presenting the current status of the physical system, DTs validate and transfer user requested positions to physical twins. Physical limitations of connected systems are defined in DTs and a programmed logic is implemented to prevent a user from moving a robot to non-permitted or out-of-reach positions. DTs are written in Javascript language and run on top of NodeJS runtime on the cloud server. DTs communication protocol to the physical world is MQTT. However, the platform supports several communication protocols to integrate a CPS. Integrating a physical system by MQTT, OPC UA, and proprietary "ARC link"-protocols have been described in this paper. Support for the aforementioned protocols is enabled by local servers at Uit and Centria laboratories. Furthermore, by writing a custom MQTT-app as described in Section 4.4.3, it is possible to connect virtually any system with an Ethernet interface to the platform.

4.6. Functionality Validation

To validate the functionality of the proposed platform, a high-level task was defined for each robot station. High-level tasks defined are specific to the robot type. For example for industrial robot's pick and place task is typical, and therefore, a simple pick and place task was defined for both industrial robots. For a collaborative robot, a task utilizing feedback of gripping force and distance was defined. A material transport task was decided suitable for the mobile robot. Tasks were planned by creating a flowchart defining the functions required for the task. A flowchart for material transport task is presented as an example in Section 4.6.3. If a defined task could be performed utilizing digital presentation, validation was considered successful, otherwise validation was considered failed. Individual validation for each robot station is described in detail in the following subsections. The goal for validation is to verify that the implementation meets functional requirements F1-F6 and non-functional requirements N1, N2, N3, N4, N9, and N15.

4.6.1. Industrial Robots

For both industrial robots, a simple pick and place task was defined. The task includes moving a cylindrical workpiece from one position to another. Conducting this task requires positioning the robot to approach, pick, place, and retract positions. Additionally, control for gripper's close and open functions is required. The correct coordinates for pick and place positions were provided prior to programming. Initial validations pointed out that functionality for the gripper state feedback was missing and the robot did not wait for the gripper to open or close before initiating the next move. Feedback functionality for the gripper was implemented and validation was successful. Figure 7 describes the cycle of the

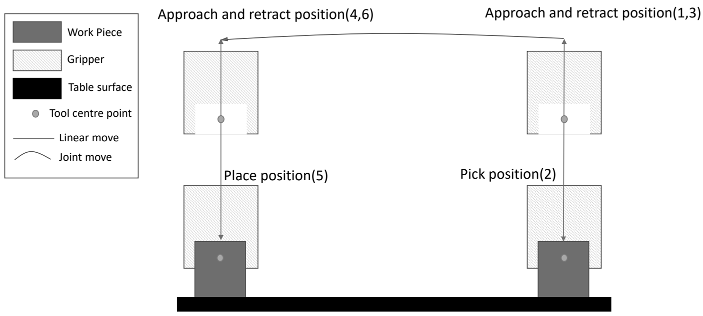

Figure 7. Program cycle of industrial robots pick and place task.

4.6.2. Collaborative Robot

For a collaborative robot, a simple assembly task was defined. The task is to press a plunger to a predefined depth of 45mm inside a solenoid housing. Programming of this task requires the utilization of linear positioning, joint positioning, adaptive gripper force, and position commands. During the validation, it was noted that the DT of the robot station did not have all functionalities required to perform the defined task. Missing functionalities of setting the gripping force and position were added to DT. Additionally, a function to switch between programming of either linear or joint move was added to pass the validation.

4.6.3. Mobile Robot

For the mobile robot, a material transport task was defined. The task requires the planned path from the park location to the loading station and from there to the unloading station. The mobile robot acts on "ready to load" and "ready to unload" messages received from two robot stations. The initial validation failed because the functionality to send and receive messages from and to robot stations was not implemented on the platform. These functions were added to the MQTT-app controlling the mobile robot and validation was successfully carried out. The mobile robot MQTT-app loading logic is described in Figure 8.

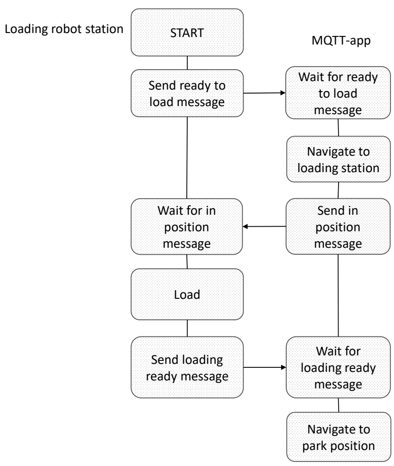

Figure 8. Mobile robot MQTT-app flowchart.

4.6.4. Scara Robot and Conveyor

For Scara and conveyor, a combined task was created to validate functionality. The objective of the task is to use the conveyor and Scara robot to interact with an object. In the task, the conveyor moves an object over to the Scara robot and the Scara robot interacts with the object. In the task, the Node-red interface is used to control both the Scara robot and conveyor and it is possible to switch between these two interfaces. The validation test showed that it is possible to make different machines interact with each other and it is easy to switch between the Node-red control interfaces.

5. Discussion

This paper utilized DTs to control equipment in two laboratories. Controlled pieces of equipment were industrial, mobile, and collaborative robot stations and a conveyor system. The overall description of the platform is presented in Figure 9. To validate the functionality, the prototype of the proposed platform was created and presented. Platform development presented in this paper opens discussions on how a common platform for teleoperation can be utilized for sharing equipment resources, creating a roadmap for cybersecure CPS, and a teleoperation platform created with open-source software. Key findings are listed in the subsections below.

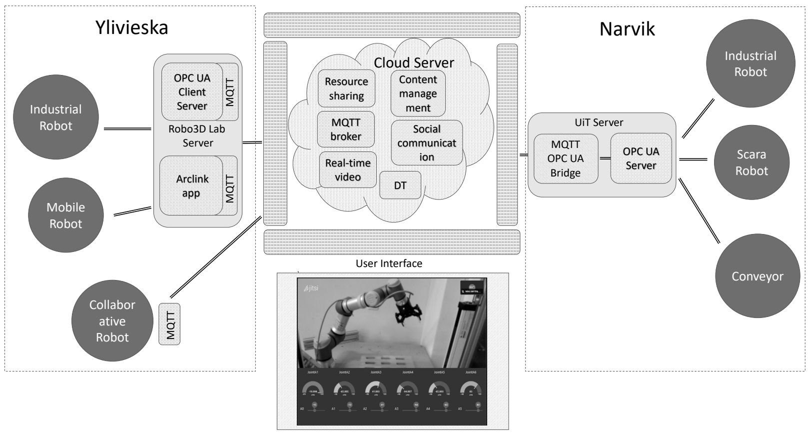

Figure 9. Implementation of proposed platform.

5.1. *MQTT Is an Efficient Communication Protocol for DT*

MQTT was chosen as the main data exchange protocol of the proposed platform because MQTT is a modern protocol based on publish/subscribe communication. MQTT allows any node to publish or subscribe to messages, providing a flexible messaging platform. OPC UA, on the other hand, is tied to the server/client communication model. MQTT communication is trivial to set up because no creation of variable structures is needed. Creating variable structures on the OPC UA communication model would be a time-consuming phase during the implementation. Utilizing the MQTT protocol does not require defining variable structures and is not tied to the client/server model.

5.2. *Latency of Video Stream Is Critical in Teleoperation*

The latency of live video stream is a critical aspect in teleoperation applications. During implementation, it was observed that latency of over 500 ms is unacceptable and has a negative impact on user experience. Choice of open source video conferencing applications based on WebRTC provides ready mechanisms for controlling video resolution to maintain latency usable for teleoperation. WebRTC has been proven to provide latency in the sub 200 ms range which was found adequate for the teleoperation of robots. Modern web browsers support WebRTC and can act as clients for near real-time video streaming.

5.3. Cybersecurity Is a Key-Enabler

CS of data transfer is a fundamental part of the online DT platform. CS aspects require consideration in the planning, development, and implementation phases of the platform. During planning it is important to select only components that are cybersecure, as one component including a vulnerability can compromise cybersecurity of the complete platform. Corruption of data can lead to unwanted movement of CPS causing damage to teleoperated CPS or the surrounding physical environment. A leak of user credentials can allow a hacker to gain control of the teleoperation interface causing intentional damage to CPS. Securing all data transfers with authentication and encryption is required to maintain data integrity. Periodic vulnerability scans have been scheduled by Centria to maintain CS since new vulnerabilities are found on a daily basis. Vulnerability scans have indicated only a few minor CS issues. The presented platform is based on open-source software and is cybersecure.

5.4. Privacy and Safety Concerns

During the development and implementation of the platform, concerns related to privacy and safety of humans physically near teleoperated CPS arose. It was noted that: (1) web cameras used to monitor CPS feature built-in microphones and can be used for eavesdropping, (2) web camera live video enables the possibility for spying, and (3) teleoperated CPS can cause physical danger to humans nearby. There are many possible solutions to overcome the mentioned privacy and safety issues. Placing the teleoperated CPS in a restricted area solves all the identified issues. In practice, especially with mobile robots, this can be challenging since a physically large restricted area for operation is required. Another option to guarantee total privacy is to offer teleoperation only outside office hours. Physical disabling of microphone hardware disables the possibility of eavesdropping but does not solve video spying or physical safety concerns.

5.5. Based on Open-Source

The platform presented was built mostly on open-source software. For many components such as CMS, video conferencing, and OPC UA communications, there are many options to choose from. Setting up open-source software for the platform presented was considered trivial. Support forums exist, and help for developing and setting up software is available. However, not all software components presented in this paper are open source: the collaborative robot MQTT-connector provided by 4Each software solutions is commercial software.

5.6. Is Teleoperation Platform Utilizing DT's Suitable for Robotics Education and Training?

The proposed platform was piloted and evaluated by a group of 20 students participating on a course of digital twins. Each student registered to the platform by providing an email address. Teleoperation, resource management, chat, and online video capabilities were tested individually and as an educational group. Students discussed on the platform, reserved time-slots for exercises, and utilized teleoperation. Teleoperation was piloted by conducting high-level tasks described in Section 4.6 as online exercises. Based on the feedback, the platform provides required functionalities and is suitable for robotics online education and training. According to the feedback, a user experience could be improved by re-designing user interfaces and adding a variety of exercises and study materials to the platform.

6. Conclusions

This paper proposed a digital twin-based teleoperation platform to control various robotics systems remotely. Full system specification and implementation details were given.

Ecological and social values, the aspects of i5.0, were included and considered during the system design. A prototype containing robot cells located geographically in two countries was implemented and reported. The proposed system allows effective resource sharing in situations where suitable devices are not or cannot be possessed but can be rented, borrowed, or otherwise used remotely. The presented resource sharing allows a single user to reserve one robot at a time for the teleoperation. In addition, the system allows multiple simultaneous users controlling different robots at same time. The proposed system is highly flexible; any cyber-physical system can be included in the platform if it supports the defined open interfaces. Because of these interfaces, the platform itself is also highly affordable.

The first steps in building a common platform for teleoperation are presented in this paper. The next possible further steps to develop the proposed platform further are discussed. Utilizing eXtended Reality-technologies(XR) as a user interface for monitoring and programming robots. To provide a platform-independent way to experience XR, a solution supporting mobile devices should be chosen. Utilizing XR would meet requirement F11 and prepare the platform for requirements F12 of virtual deployment and N16 of gamification.

Improving support for mobile devices would increase the accessibility of the platform. Currently, accessing some functions of control interfaces may require scrolling and zooming of view, affecting the user experience negatively. To improve user experience, teleoperation and CMS layouts should be re-designed and re-implemented. Adding functionality for online examination and providing certificates would enable utilizing the platform for certified training and education, meeting requirements F9 and F10.

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PUBLICATION V

Digital Twins Utilizing XR-Technology as Robotic Training Tools

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Article

Digital Twins Utilizing XR-Technology as Robotic Training Tools

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Abstract: Digital technology has evolved towards a new way of processing information: web searches, social platforms, internet forums, and video games have substituted reading books and writing essays. Trainers and educators currently face the challenge of providing natural training and learning environments for digital-natives. In addition to physical spaces, effective training and education require virtual spaces. Digital twins enable trainees to interact with real hardware in virtual training environments. Interactive real-world elements are essential in the training of robot operators. A natural environment for the trainee supports an interesting learning experience while including enough professional substances. We present examples of how virtual environments utilizing digital twins and extended reality can be applied to enable natural and effective robotic training scenarios. Scenarios are validated using cross-platform client devices for extended reality implementations and safety training applications.

Keywords: digital twin; extended reality; robotics

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1. Introduction

The digital-native generation of today requires new ways of training and education [1–4]. Compared to previous generations, who grew up reading literature and comics, digital-natives have grown up surrounded by digital appliances, including cell phones, computers, and video games [5,6]. Growing up with the possibilities of new digital technology, a new way of processing information has evolved: instead of reading books and writing essays, digital-natives learn by utilizing web searches, social platforms, and internet forums. Digital natives prefer browsing graphical and video content over reading text documents; the new way of learning is more technological and digitally oriented. Trainers and educators of today are facing the challenge of providing training and learning environments natural for digital natives. In addition to physical spaces, effective training and education require cyberspaces [7]. An environment natural to the trainee supports the learning process, providing a positive learning experience and outcome. In this paper, virtual environments (VEs) utilizing extended reality (XR) are experimented on to enable natural and effective training environments for the digital native generation.

VEs are one of the most popular ways of interacting with each other for digital natives [8]. VEs enable simulations and demonstrations impossible to implement in a traditional classroom, bound to physical and geographical constraints. XR divides into sub-categories of augmented reality (AR), augmented virtuality (AV), and virtual reality (VR) [9]. AR, AV and VR enable the creation of immersive and augmented realistic training environments for the digital-native generation. AV and AR enrich virtual and real environments by adding real-world elements to the virtual world or virtual elements to the real world, creating mixed reality (MR) training experiences. VR enables an immersive training experience where the trainee immerses in a virtual environment. While XR currently applies to a wide variety of training applications, only a few aim for remote training of basic robotic skills. Furthermore, extensive studying of AV implementations for robotic training is required. XR enables risk-free remote training for controlling, programming, and safety of industrial robots. The benefits of safety training in a simulated environment have been known for decades [10]. Morton Heilig stated in his patent application that the training of potentially hazardous situations and demanding industrial tasks should be carried out in a simulated environment rather than exposing trainees to hazards of the real environment.

A fully simulated training environment does not provide a realistic experience to the trainee; therefore, interfacing with real equipment is required [11,12]. If the trainee is allowed to control real equipment and see the results in a real environment, training experience is very close to hands-on experience. Digital twins (DTs) enable the user to interact with real hardware utilizing VEs, providing a bidirectional communication bridge between real and virtual worlds [13]. Real-time data such as speed, position, and pose from physical twins to digital twins instead of simulated data enable a realistic training experience. In addition, augmenting data of the surrounding environment to digital twin is possible [14,15]. Furthermore, DTs enable the validation of data such as robot trajectories before committing data to real hardware, enabling safe teleoperation of robots [16]. In the system proposed in this paper, DTs enable trainees to interact with real-world robot hardware. After validating the trajectories created by the user, DTs pass trajectories to the physical twin, and the physical twin provides feedback sensor data to DT. The proposed solution is intended as a virtual training environment, not as a robotics simulator such as Gazebo [17] or iGibson [18].

The industry is starting to implement the Metaverse, utilizing DTs as the core [19]. By creating DTs of physical equipment, virtual spaces, and data communication in between, the first steps towards the Metaverse are taken [20]. The Metaverse has the potential to merge physical reality and digital virtuality, enabling multi-user VEs. The latest implementations of the industrial Metaverse include training, engineering, working, and socializing [21].

In our previous work, we proposed a common teleoperation platform for robotics utilizing digital twins [22]. This paper extends our previous work by adding VEs to the proposed platform, enabling virtual training for basic robotic skills such as manual control and safety functionalities of industrial robots. The research question is: What are the benefits and challenges of DT and XR in remote robotic training? The contributions of this publication are as follows:

1. Three XR training scenarios for robotic safety, pick and place, and assembly.
2. Web-based XR architecture to support cross-platform functionality on both desktop and mobile devices.
3. DTs enabling teleoperation and trajectory validation of physical robots.

The paper is organized as follows: Section 2 explains methods and approach, including requirement specification for the proposed VEs. Section 3 provides a review of previous research of the topic. Section 4, describes the implementation and validation of proposed VEs. Section 5, provides further discussion of the results. Section 6 provides the conclusion of this publication.

2. Methods and Approach

This section presents methods utilized during the development of the proposed solution. The planning phase includes requirement specifications for the XR-training environment. Section 2.1 presents requirements specified for VEs, providing a fundamental guideline for the implementation described in the Section 4. The first task of the development phase is to define and validate the system architecture. After defining the architecture, the development continues with the implementation. The implementation consists of iterative modeling, programming, and functionality validation tasks. The validation task consists of three training scenarios to validate the functionality of VEs. The first training scenario studies the utilization of augmented virtuality in a traditional pick-and-place task. The second training scenario utilizes augmented reality to visualize industrial robot reachability, and the third scenario enables an immersive human–robot collaboration safety training experience. After validating VEs against the requirement specification, VEs are considered ready for evaluation in real training applications. Figure 1 presents the methodology utilized in this work for planning, developing, and implementing the proposed VEs. Table 1 presents requirements specified for the VEs.

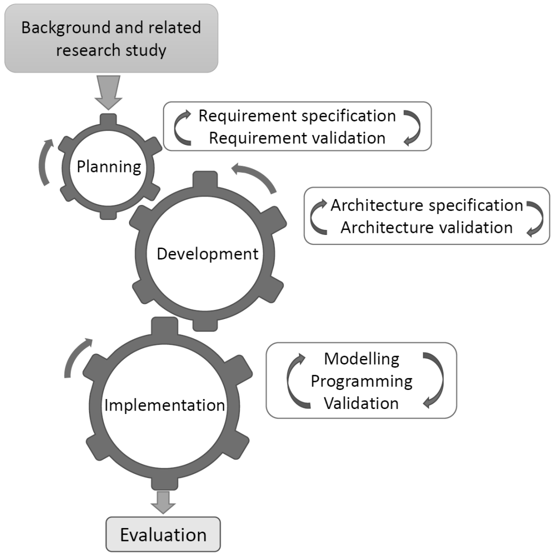

Figure 1. Methodology used in this work to develop and validate virtual environments. The foundation for planning is based on published results in the field and close collaboration with the industry. In the planning phase, requirements for the system are defined. Based on the specification, the system architecture is developed and validated. During the iterative implementation, the system is built and validated for the final evaluation.

Table 1. Requirements specified for virtual environments.

ID	Description	Category
N1	The systems clearly focuses on robotics.	Usability
N2	Platform independent.	Usability
N3	CS is considered. Remote users cannot access the system without authentication. Additionally, robot functionality is restricted for safe operations.	Security
N4	Safety taken into consideration in remote usage.	Security
N5	System updates and upgrades do not require actions from end-user.	Usability
N6	Delay between virtual and physical robots should be less than 250 ms.	Performance
N7	Exercises can be in a form of a 3D experience or desktop game.	Usability
N8	Specific VR-devices are not required	Usability
N9	User can teleoperate and program robots	Usability

2.1. Requirement Specification

The authors of this paper, having pedagogical, XR, robotics, and software development backgrounds, specified requirements for the VEs. The requirements specified are non-functional, defining quality-related requirements, such as how long the delay is between DT and the physical twin. The requirements were divided into sub-categories of usability, security, and performance, depending on the nature of the specific requirement. Security requirements consider cybersecurity and physical security issues since a cybersecurity breach can compromise both. The requirements presented provide a fundamental guideline for the implementation phase.

3. Background and Related Research

The related research study aims to investigate and select hardware and software components required to build DTs utilizing XR technology as robotic training tools. The chosen components are required to meet requirements specified in Section 2.1. An overview of research on virtual reality and digital twins is provided, with a focus on the training of robotics. A study of XR hardware and software provides essential information on available tools to create and experience VEs and to select the correct tools for our implementation.

3.1. Extended Reality

Extended reality has been an active research topic for decades; in the early days, a common term was artificial reality instead of extended reality. The first steps towards providing a VR experience were taken in 1955 when Morton Heilig published his paper "The cinema of the future" describing a concept for a three-dimensional movie theater [23]. Later in 1962, Heilig presented The Sensorama, a device based on his concept providing the user with an immersive three-dimensional experience. Sensorama enabled the user to sit down and experience an immersive motorcycle ride through New York [24]. In addition to the visual experience, Sensorama provided the user with sensations of scents, vibration, wind, and audio [25]. Sensorama met all characteristics of virtual reality except one since the filmed route was static. Sensorama lacked interactivity, an essential element of virtual reality [26,27]. NASA's Virtual Visual Environment Display (VIVED), introduced in the early 1980s, was the first head-mounted display (HMD) documented to enable all characteristics of virtual reality: interaction, immersion, and imagination. The term virtual reality was introduced by Jaron Lanier later in the eighties [28]. Lanier's company VPL Research a spinoff from NASA, developed and marketed several XR devices including, EyePhone, Data Glove, and Data suit. EyePhone was one of the first commercially available VR headsets.

Augmented reality was first presented in 1968 by Ivan Sutherland as "A head-mounted three-dimensional display" [29]. While HMDs for applications such as video surveillance and watching TV broadcasts had been proposed earlier [30–32]. Sutherland's contribution was to replace external video feedback with computer-generated graphics, and the first interactive AR system was born. Due to limitations set by the computing power of the era, Sutherland's system was capable of providing only three-dimensional wireframe objects in front of the user's eyes. The term augmented reality was coined later by Tom Caudell in 1990 when he was investigating see-through HMDs for tasks related to aircraft manufacturing [33].

Myron Krueger [34] studied augmented virtuality in his project "responsive environments". Krueger's idea was to create a telepresence concept that would provide a virtual space where people distant from each other could interact in a shared virtual space. Krueger's Videoplace experiment consisted of rooms with a projector, a sensing floor, and a camera as a motion-detecting device to capture user movements and gestures. Videoplace enabled an augmented virtuality experience, augmenting the user into a virtually generated shared experience projected onto the walls of all connected rooms.

Virtual-Reality continuum, presented by Paul Milgram in 1994, defines XR as the main category for all technologies, including virtual objects [9]. Augmented reality and augmented virtuality form a subcategory of XR called Mixed Reality. Figure 2 clarifies XR and related subcategories.

AR, AV, and VR environments are implemented, presented, and discussed in this paper. Discussion Section 5 presents a comparison between entirely virtual and augmented training environments.

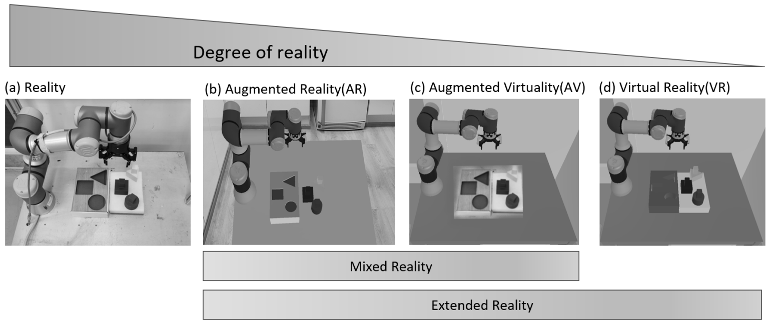

Figure 2. Reality–virtuality continuum. (**a**) real environment, (**b**) augmented virtuality, (**c**) augmented reality, and (**d**) virtual reality. The degree of reality decreases when moving from a real environment to virtual reality.

3.2. Extended Reality Hardware

Modern devices enabling XR-experiences are a result of long-term development work of researchers and innovators in the fields of entertainment [10], optics [35], electronics [36], and computing [29]. Immersive experience requires a minimum field of view (FOV), refresh rate, and resolution. Achievements in optics contribute to providing FOV wide enough to cover the entire area the user can see to provide an immersive virtual experience [26,35,37]. If the user can see a glimpse of the VR-headset frame instead of the virtual scene, the sense of immersion distorts immediately. Tracking the movement of the user's head and adapting perspective accordingly also contributes to creating a sense of immersion for the user [25]. User movement tracking systems can be either integrated or external to/of the headset [38,39]. Current external tracking systems enable twice as large a play area for the user compared to integrated tracking systems. Evolution in display technologies enables light, high-resolution display units capable of providing realistic graphics quality [24]. HMDs, now known as VR headsets, combine optics, displays, tracking devices, and speakers, into one product enabling an immersive virtual reality experience. VR headsets are capable of both standalone operation without a PC and operating as a connected accessory to a PC. Headsets connected to a PC can utilize high-end graphics processors and wired or wireless connections between PC and headsets [40]. Wireless VR headsets free the user from hanging cables, enabling the user to move freely within the limits of the play area. Current high-end systems such as Varjo XR-3 released in 2021 enable high-resolution wide field of view augmented, virtual and mixed-reality experiences [41]. The most affordable devices to experience extended reality are mobile phones and tablets. Mobile devices enable support for augmented reality by utilizing built-in position sensors and camera units. An immersive VR experience requires Google cardboard or similar VR-headset casing and the mobile device itself. A combination of mobile devices and Google Cardboard provides an affordable way to experience extended reality with the cost of lower FOV and resolution specifications compared to purpose-built devices. To ensure cross-device compatibility and to compare the significance of resolution, refresh rate, and FOV in training applications, VE implementations in this paper are validated utilizing Oculus Quest(Meta Platforms, Inc., Menlo Park, California, USA), HTC Vive(HTC Corporation, Taoyuan City, Taiwan) and Varjo XR-3 VR(Varjo Technologies Oy, Helsinki, Finland) headsets. A comparison in Table 2 presents the specifications of VR headsets. Specifications of the early EyePhone provide a baseline for comparison.

Table 2. Technical details of VR-headsets .

System	AR/VR	Year	Resolution	Weight	FOV	Tracking
EyePhone [24,26]	VR	1989	360 × 240	2400 g	90H × 60V	external
HTC Vive [39,42]	VR	2016	1080 × 1200	563 g	110H × 113V	external
Oculus Quest I [40]	VR	2019	1600 × 1440	571 g	115H × 90V	internal
Varjo XR-3 [41]	AR/VR	2021	2880 × 2770	980 g	115H × 90V	both

3.3. Web Based Extended Reality

Web-based XR applications are accessible, cybersecure, and not tied to specific hardware platforms or devices meeting non-functional requirements N2 and N3. Furthermore, the updating or upgrading of web-based applications does not require any user actions meeting requirement N5. For the aforementioned reasons, the web-based approach is chosen as the implementation for the VEs proposed. This section presents standards and protocols related to building web-based XR applications.

HTML5 is the latest version of HyperText Markup Language (HTML) released in 2008 [43]. HTML5 provides the user with advanced functions such as local file handling and support for complex two- and three-dimensional graphics [44]. HTML5 enables the embedding of three-dimensional graphics inside a Canvas element on any web page. Canvas application programming interface (API) provides a rectangular element as a graphics container on a web page. The graphic content creation inside the canvas element is enabled utilizing JavaScript. JavaScript is well known as a lightweight scripting language for web pages. JavaScript enables the real-time update of graphic content inside the Canvas element.

Web Graphics Library (WebGL) JavaScript API is capable of producing hardware-accelerated interactive two- and three-dimensional graphics inside the HTML5 canvas element. Together, WebGL and HTML5 canvas enable presenting three-dimensional interactive graphics embedded into a web page. Furthermore, the standards enable cross-platform XR-application development for desktop and mobile devices.

The WebXR device API (XRDA) standard enables a platform-independent interface to access hardware required for interactive XR-experience [45]. XRDA provides access to extended reality device functionalities such as the pose or position of the controller, headset, or camera and utilizes WebGL to render augmented or immersive virtual graphics accordingly. WebXR enables an extended reality experience on a desktop PC or a mobile web browser [46]. Figure 3 describes the structure of a WebXR-application.

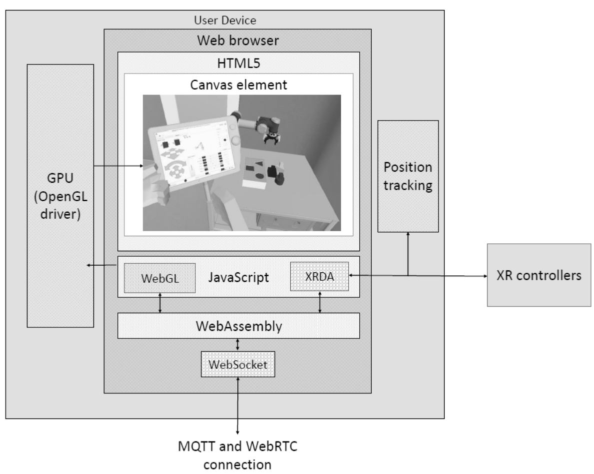

Figure 3. Structure of WebXR-application.

WebAssembly (Wasm) is a binary instruction format for a stack-based virtual machine. Four major browsers support Wasm to provide native speed execution of web-based applications [47]. During compilation, native formats such as C#, C++, and GDScript compile into Wasm format. As Wasm code does not have access to hardware, Javascript code is required to enable access to XR devices and graphics processing unit (GPU). The latest versions of the popular HyperText Transfer Protocol (HTTP) server Apache provides server-level support for Wasm [48].

3.4. Digital Twin Concept

Michael Grieves presented the concept of DT in 2002 as a conceptual idea for Product Lifecycle Management (PLM) [49]. The conceptual idea includes a virtual and real system linked together from the design phase to the disposal of the product. DT definition has been evolving since, and a virtual copy of a physical system enabling bidirectional interaction is one of the definitions [50]. Kritzinger defined automated bidirectional data flow as a unique feature of a DT, distinguishing DT from digital shadow and digital model [51]. Digital twin consortium defined data flow as a synchronized event at a specified frequency [52]. Automated data flow is an essential element of the DT concept, enabling interaction with the low-level functions of the physical twin and digital presentation of the physical twin information. DTs can present an individual system such as a robot or larger entities such as factories, supply chains, and energy systems [53–55]. In 2021, the International Organization for Standardization (ISO) defined standards for DT framework [56]. The concept of the DT has recently matured into a standardized framework. In this paper's context, DTs enable interaction between the virtual training environment and physical robots.

3.5. Bidirectional Communication

WebSocket protocol provides a single bidirectional Transmission Control Protocol (TCP) connection from a web application to the server [57]. The WebSocket protocol is suitable but not tied to online gaming, stock exchange, and word processing. In the context of the proposed system, WebSocket enables data connections between an MQTT-broker on a cloud server and the user web application. The protocol enables both encrypted and unencrypted connections. In the proposed VEs, an encrypted connection method enables cybersecurity and meets the requirement N3. The WebSocket protocol support was added to the MQTT standard in 2014 [58], enabling MQTT messaging for web applications. In addition to the standard, also OPC Unified Architecture (OPC UA) standard is used to communicate with the hardware. OPC UA is an open cross-platform IEC62541 standard for data exchange [59]. OPC UA is a widely utilized industrial communication standard and Industry 4.0 reference standard [60,61].

3.6. Real-Time Video

Web Real-Time Communication (WebRTC) is an open-source technology for real-time web-based communication [62]. Considering projected real-world elements in the AV experience, delays in video transmission affect the user experience and may cause the user to misguide the robot during a task. Major web browsers support WebRTC on mobile and desktop devices.WebRTC meets the requirement N6 with proven Round Trip Times of 80 to 100 milliseconds on mobile platforms [63]. WebRTC utilizes User Datagram Protocol (UDP) for video data transfer. Since UDP does not support congestion control, the WebRTC server component on the cloud server is required to control the congestion.

3.7. Extended Reality Software

This section evaluates three game engines to choose the game engine to build extended reality training environments meeting the requirement specification defined in Section 2.1. The focus is on ease of distribution and updating of applications, accessibility, and cross-platform support. Epic's Unreal Engine (UE), launched in 1998, is widely utilized in various industrial applications [64]. UE provides methods for programming functionality of VEs:

using C++ or Blueprints. While Blueprint is an easy-to-use visual tool for scripting design, C++ enables programming more complex functionalities. Official releases of UE do not include support to build WebGL runtimes; instead, UE version 4.24 at GitHub supports compiling WebGL runtimes. Unfortunately, the UE GitHub project page was closed during the writing of this paper, preventing utilizing UE4 as a game engine for the proposed VEs.

Unity Technologies released the Unity3D development platform in 2005 as a game engine for macOS. Currently, Unity3D is one of the most popular game engines for desktop and mobile devices [65]. Unity3D includes physics and rendering engines, asset store, and graphical editor [66]. Visual Studio integrated development environment is utilized to program functionality with C#. Unity3D is a cross-platform game engine enabling compiling of XR applications for Windows, macOS, Android, and WebGL. The online asset store provides a wide selection of contributed components as importable assets, enabling functions such as web browsers, interaction toolkits, and connections to various physics engines. For the MQTT connectivity, Best MQTT-asset for Unity3D written by Tivadar György Nagy can be utilized [67].

Open source game engine Godot [68,69] was released under an MIT license in 2014 as an open-source alternative for Unity3D. Godot comes in two versions, the Mono version supports C#, and the native version supports GDScript language. Compiling both C# and GDScript projects is currently supported only for desktop systems; mobile applications support only GDScript. Godot engine provides an asset library and a graphical scene editor. The Godot editor user interface is very similar to the Unity3D editor, providing views of the hierarchy, scene, and properties of objects. Godot supports the cross-platform building of XR applications for Windows, Linux, iOS, macOS, Android, and WebGL [70]. Currently, Godot does not support Websocket MQTT-protocol, and implementing one is beyond the scope of this publication.

Unity3D is the choice for this project since it supports multiple features required to meet the requirement specification. Unity3D enables the compiling of Web-based XR applications, providing platform independence, easy distribution, and accessibility required in N2, N5, N7, and N8. In addition, support for the MQTT protocol enables the bidirectional communication required by N9.

3.8. Extended Reality in Robotic Training

The industry utilizes XR for various industrial training purposes such as mining [71], construction [72,73], and maintenance [74,75]. Applying XR for the training of industrial robot programming and operating tasks has the potential to provide effective training environments. In 1994 Miner et al. [76] developed a VR solution for industrial robot control and operator training for hazardous waste handling. VR solution enabled trainees to create robot trajectories in an intuitive way and, after validation, to upload trajectories to the real robot. Operators tested the solution, and according to their feedback, the system was easy to use. A few years later, Burdea [77] researched the synergy between VR and robotics. Burdea found the potential of VR in the training of robot programming and teleoperation tasks. He described VR robot programming as a user-friendly, high-level programming option for robots compared to the low-level programming method provided by a teach pendant. Furthermore, the robot arm can act as a haptic feedback device, providing force feedback to the user. Crespo et al. [78] implemented and studied a training environment for off-line programming training of an industrial robot. They developed an immersive solution capable of evaluating trajectories created by the user by calculating the shortest collision-free path and comparing the shortest path to the path created by the user. This study supports the results of Miner et al. in terms of enhancing the learning of robot programming and reducing programming time. Perez et al. [79] created a VR application for industrial robot operator training. According to the feedback collected from the pilot users, VR training was user-friendly and reduced the time required for training. The study also proved VR as a risk-free realistic programming method for industrial robots. Monetti et al. [80] compared programming task completion time and task pass rate utilizing VR and teach pendant on a real robot. The pilot group consisted of twenty-four students who had novice skills in robot programming and performed programming tasks quicker and with a higher pass rate than those utilizing a teach pendant. Dianatfar et al. [81] developed a concept for virtual safety training in human–robot collaboration. The prototype training environment enabled the trainee to visualize the assembly sequence and shared workspace and to predict robot movements. Virtual training enabled comprehensive training of both experienced and inexperienced robot operators. Bogosian et al. [82] demonstrated an AR application enabling construction workers to interact with a virtual robot to learn the basic operation of a robot manipulator. Rofatulhaq et al. [46] developed a web VR application to train engineering students utilizing a virtual robot manipulator. The reviewed papers provide good examples of the ongoing toward utilizing XR for training in the architecture, engineering, and construction sectors (AEC).

4. Implementation and Validation

This section presents the implementation and validation of the VEs. First, we present a description of the system architecture. After describing system architecture, descriptions of individual VE implementations are provided, and finally, validation of VEs. This section provides practical information on implementing VEs similar to the ones presented in this paper.

4.1. System Architecture

The system architecture specification results from requirements specified in Section 2.1 and software components selections explained in Section 3. The central part of the system proposed is a cloud server hosting an MQTT-broker to publish/subscribe messaging between physical and digital twins and to enable congestion control for WebRTC video stream. The Robo3D Lab server connects to the cloud server and acts as a data bridge between hardware and the cloud server. The user device is the device a trainee utilizes to interact with VE and DT. Descriptions of individual VE Implementations are in Sections 4.2.1–4.2.3. Figure 4 describes the connections of the architecture in detail. The user device can be any device capable of running an HTML5-enabled web browser, enabling the trainee to interact with the VE.

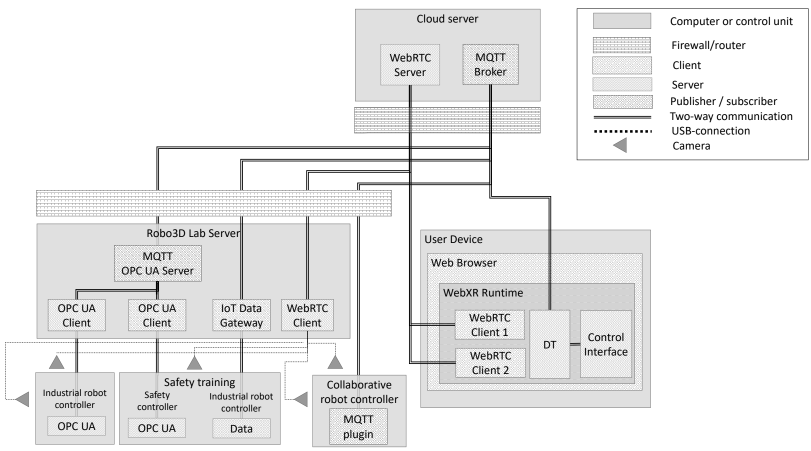

Figure 4. System architecture.

4.2. Robo3D Lab

The implementation of the XR environment started by utilizing an industrial-grade three-dimensional laser scanner to form a point cloud of Robo3D Lab located in Ylivieska, Finland. Based on the point cloud data, a three-dimensional solid model was created and textured utilizing Blender. Features such as walls, floors, ceilings, pillars, windows, and doors were extruded and cut to match the raw point cloud data. Modeling the basic shapes was followed by overlaying textures to create a realistic virtual training environment. After texturing objects, virtual light sources, reflections, and shadows were added to the scene. Removing the original point cloud data and exporting the model to Unity3D were the last required steps. The three-dimensional model of Robo3D Lab is not a replica; redesigned textures create a modern virtual version.

The Robo3D Lab model was imported into an empty Unity3D project Universal Render Pipeline (URP) template. URP supports cross-platform optimized graphics [83]. The WebXR Exporter [84] asset enables the trainee to interact with the virtual environment, providing required template objects for an in-person player. The VR-toolkit asset enables the teleporting of the player and game objects inside Robo3D Lab. Figure 5 presents a view of the empty Robo3D Lab created with Unity3D as the main VE for the training environment. The following subsections present three robotic training scenarios created inside the main Robo3D Lab VE.

Figure 5. View of Robo3D Lab virtual environment.

4.2.1. Augmented Virtuality Training Scenario

The environment for the AR pick-and-place exercise consists of digital and physical twins of the robot cell located in Centria Robo3D Lab. The physical twin is a collaborative robot (Universal Robots A/S, Odense, Denmark) equipped with an adaptive two-finger gripper. The robot is on top of a table, and the robot control unit is under the tabletop. The objects manipulated in the pick and place training task, a 3D-printed cube, cylinder, and triangular elements, are on the table in front of the robot. Furthermore, a white cardboard box with precut holes for each element is between the robot and the 3D-printed elements.

Three-dimensional model files and dimensional data of the robot arm are required to create a digital model of the robot. Model files and dimensions of the robot arm are from a ROS-industrial universal robot package at GitHub [85]. The teach pendant model file is from the Universal Robots' online library. Model files were modified, textured, and exported to Unity3D utilizing Blender. Furthermore, a screenshot of the Universal Robot jog screen is overlaid on the pendant model to provide an authentic user interface to the trainee. The functionality of the user interface integrates into teach pendant game object, written in C#-script. The functionality is common for arm robots: joint and linear jog buttons inch the robot into the desired direction with a preset velocity. In addition to the jog function, the user interface enables gripper open and close functionality. Blender was utilized to model, texture, and export three-dimensional model files to Unity3D.

As the trainee fully immersed in VR cannot visualize the pose or position of elements, the augmentation of elements from the real world to the virtual experience is required. For this purpose, two web cameras provide a live video stream from top and side perspectives of the 3D-printed elements and cardboard box. The video streams to the XR-training environment utilizing WebRTC over a WebSocket connection. The video projects to the table surface in Unity3D. Projecting positions of the elements and the cardboard box to the trainee. Figure 6 presents a video projected on the table surface. To transfer and project the video onto the texture on the table surface, we utilize code provided by AVStack (AVStack

Pte. Ltd., Singapore) [86]. The accurate position and pose of the elements are required to complete the pick-and-place task successfully.

MQTT-connector provided by 4Each software solutions(4Each s.r.o., Praha, Czech Republic) is installed on the collaborative robot controller to enable bidirectional communication. MQTT-connector enables publishing and subscribing to robot data, enabling communication between physical and digital counterparts.

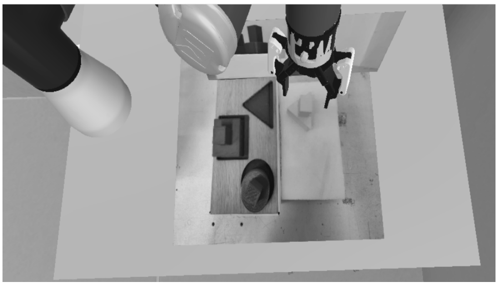

Figure 6. View of Augmented Virtuality setup.

4.2.2. Augmented Reality Training Scenario

The AR implementation consists of digital and physical twins of a Fanuc Educational robot cell (Fanuc Corporation, Oshino-mura, Japan). The robot cell consists of an aluminum profile frame, robot arm, robot controller, machine vision camera, and a two-finger gripper. Additionally, 3D-printed cube elements are included as objects to manipulate. Model files and dimensions of the robot arm are from the ROS-industrial universal robot package at GitHub [85]. Model files of robot 3D-printed elements for exercise were created, textured, and exported to Unity3D utilizing Blender.

The user interface to control the robot utilizes a touch screen typical for mobile devices. The trainee can drag the robot into different positions by simply dragging Tool Center Point (TCP) to the desired location. Buttons overlaid on the AR scene enable the gripper open and close functionality. The functionality of the touch-based user interface to control the robot and the gripper is written in C#. The touch interface provides an intuitive way to control the projected AR robot. In addition to the augmented virtual robot, the trainee can observe a live video stream of the physical robot.

Fanuc Robot controller does not support the MQTT protocol; instead, the robot controller supports the industry-standard OPC UA protocol. A custom OPC UA to MQTT-bridge based on Open62541 [87] enables bidirectional communication between the digital and physical twin of the robot. Figure 7 presents the implemented AR visualization of the robot arm.

Figure 7. Augmented Reality with visualization of robot working area.

4.2.3. Virtual Reality Safety Training Scenario

The physical twin is an industrial production cell consisting of an ABB IRB6700 industrial robot (ABB Ltd., Zurich, Switzerland), safety fences, a safety control panel, safety light curtains, safety laser scanners, and an apartment floor structure. Model files for the robot were obtained from the manufacturer's website and imported into Unity3D with Blender. Model files for the safety light curtains, laser scanners, and safety control panel were created and textured utilizing Blender. A local building manufacturer provided a digital model of the apartment floor structure in an industry-standard Building Information Model (BIM) format. Blender was utilized to import the BIM texture elements of the floor structure and export the textured floor structure into Unity3D. The safety control panel three-dimensional model exported to Unity3D Scene is overlaid with a screenshot of the physical safety control panel. The overlaid screenshot provides the user interface for controlling the robot and safety device functions. The functionality of the safety controller consists of resetting the tripped safety devices and restarting the robot's operation cycle. Violation of the robot operation area is possible from three directions, two safety light curtains and a laser scanner monitor mentioned directions. Figure 8 presents the setup of safety training VE.

ABB Robot controller option "IoT Data Gateway" enables OPC UA and MQTT protocols. The ABB "IoT Data Gateway" option requires client software to act as a gateway between the robot controller and the internet. The ABB client software is installed on the Robo3D Lab server and configured to publish and subscribe robot positions, speed, and gripper states to and from the MQTT broker installed on the cloud server.

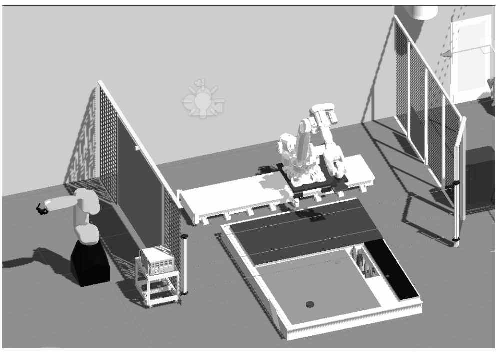

Figure 8. View of Unity 3D scene for safety training.

4.2.4. Digital Twinning

DTs provide the trainee with a way to interact with hardware connected to VEs. Each of the aforementioned digital robots has a physical counterpart and connection in between. DTs of the industrial robots are based on Unity3D Inverse Kinematics (IK). The inverse kinematics solution utilizes the Jacobian matrix to calculate joint values to achieve the requested TCP position. The forward kinematic solution utilizes Denavit–Hartenberg (D-H) convention. Publications presenting utilization of both forward and inverse kinematics calculations for various robot arms are available [88–91] and are used as a basis for the solution presented here. Figure 9 presents the inverse kinematics logic utilized in this work. The rigging of the industrial robot mechanics was created with Blender and imported into Unity3D along with model files. The rigging was utilized in Unity3D to create a kinematic model to bind robot arm mechanical elements together with constraints equivalent to the physical robot. IK calculations are based on the model, preventing moving the robot to non-wanted or out-of-reach positions. The table and walls surrounding the physical robot were also created in Unity3D and defined as physical barriers, limiting the robot's movement inside these barrier elements. DTs presented enable three levels of integration with physical twins: digital model, shadow, and twin. The trainee can select between the three levels of integration for the DTs, utilizing the XR interface.

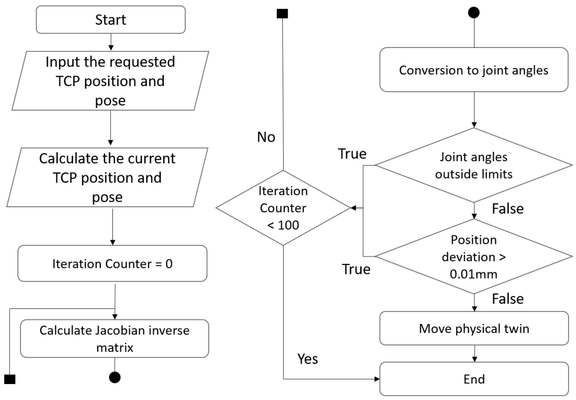

Figure 9. Flowchart of inverse kinematics logic.

Digital and physical twins of industrial robots communicate utilizing the MQTT protocol. Communication utilizes Best MQTT-asset and C#-language. Example code files provided with assets were modified to create a bidirectional communication link between the twins. MQTT is the main protocol of this implementation; however, the implementation does not limit to MQTT. The implementation supports OPC UA and proprietary communication protocols by utilizing a custom bridge described in Section 4.2.2. Enabling the connection to virtually any production machine with control over Ethernet communication.

4.3. Functionality Validation

To validate the functionality of the XR training environment, a high-level task was defined for each of the aforementioned scenarios. Validations were performed against the defined requirement specification defined in Section 2.1. To validate cross-platform support of the application, HTC Vice and Oculus Quest devices were utilized for immersive VEs. iOS tablet device and Android phone were utilized in the functionality validation of the AR implementation.

4.3.1. Augmented Virtuality Training Scenario

For the collaborative robot, we defined a simple pick-and-place task. The goal for the validation task is to pick up the cube, cylinder, and triangular objects from the table and place them into the precut holes of the cardboard box. The task requires programming the robot to approach, pick, place, retract, and control the gripper functions.

The initial functionality validation failed because controller button definitions differ between Oculus and Vive: the physical button layout is not identical. Button definitions in Unity3D C#-scripts were re-implemented to support controllers from both manufacturers. All the functions, such as teleporting and jogging of the robot, are mapped to the joystick on Oculus controllers and touchpad on Vive controllers, providing a similar user experience for both devices. The first implementation for jogging the robot enabled controlling the robot by inching the DT. Due to delays in data transfer, this implementation method resulted in a poor user experience. Replacing the inching method with a method enabling the trainee to initiate the DT movement after inching the digital model of the robot to the desired end position resolved the issue. If the DT validates the end position initiated by the trainee, the end position passes to the physical robot. The mentioned implementation was accepted and chosen for the final evaluation. Validation pointed out that the gray color of the cube element was hard to distinguish from the black-colored gripper. Replacing the gray cube element with a red cube simplifies the training task. After re-implementing controller button mappings, the color of the cube, and the method for the jogging of the robot, validation of the VE was successful.

4.3.2. Augmented Reality Training Scenario

A three-dimensional AR model of the robot, gripper, 3D-printed elements, and wire-frame visualization of the robot's working area form a training task for the industrial robot. This task aims to assemble the 3D-printed cube, triangle, and cylinder objects into a pile utilizing tabs and notches printed onto the objects. The trainee can augment the AR model to any physical environment and create a program for the robot to manipulate the cube elements. This task requires program the robot to approach, pick, place, retract, and control the gripper functions. The challenging part of this exercise is the short reach of the robot, requiring accurate planning of robot trajectories to pile all 3D-printed elements on top of each other.

The initial validation for this exercise failed because controlling the robot with the touch screen is inaccurate, making it impossible to accurately position the 3D-printed elements on top of each other. This part of the exercise was re-implemented by creating snap points for each of the 3D-printed elements in Unity3D. Snap points enabled the trainee to guide the robot by clicking pre-defined points in the scene. After adding snap points, the validation was successful.

4.3.3. Virtual Reality Safety Training Scenario

A human–robot collaboration training task was defined to validate the functionality of the safety training VE. The task requires the trainee to insert HVAC piping and a layer of glue onto the floor structure during the apartment floor manufacturing process. The trainee is signaled by a green light when to enter the robot cell to add glue and HVAC-piping between the robot work cycles. After performing manual operations, the trainee must press a button on the safety controller screen to continue the robot's operation. If the trainee interferes with the robot cell area during the robot work cycle, the safety device is triggered, and the robot motion stops. The trainee must reset the alarms on the safety controller and the robot controller to restart the robot.

The initial validation failed because the triggering of virtual safety devices caused the physical robot to halt during motion. The implementation was modified so that the physical robot does not halt; instead of causing a halt on the physical robot, only the DT halts. After resetting the virtual safety controller and restarting, the DT continues synchronizing its motion with the physical robot. The validation was successful after this modification.

5. Discussion

This paper presented three XR robotic training scenarios designed to support the digitally oriented learning process of digital-native trainees. To enable location and time independence, web-based VEs were designed and implemented. MQTT protocol enables bidirectional communication between the digital and physical twins of the robots. Figure 10 presents the configuration of the physical and digital training environment. To validate the functionality of developed VEs, prototypes of training environments were created and tested. Prototypes of VEs presented open up a discussion on the benefits and challenges of utilizing DTs and XR for robotics training. The key findings of the authors are listed in the following subsections.

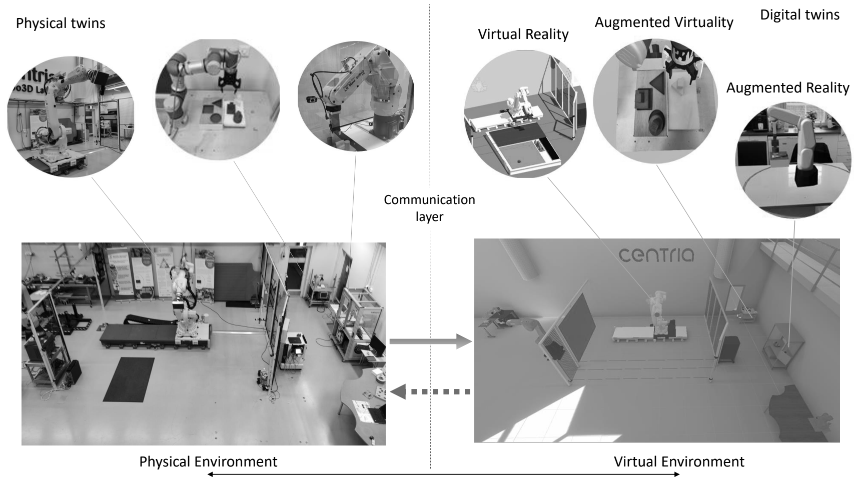

Figure 10. Physical and virtual training environment.

5.1. Augmented Virtuality Enables Virtual Teleoperation

AV enables the augmenting of real-world elements to the virtual world. The added value is providing interactive object data from the real world to the trainee fully immersed in VR. In addition, AV enables environment-aware teleoperation of industrial equipment such as robot manipulators. In this publication, AV implementation augmented side and top views of real-world elements to VR. The proposed method enables near real-time update of element positions and effective user experience. This exercise allows the trainee to fully immerse into a high-fidelity environment provided by VR and concentrate on the exercise itself rather than spending time and effort understanding the platforms. Furthermore, DT enables interaction which utilizes real hardware to perform specific tasks, such as picking and placing 3D-printed objects with an industrial robot manipulator.

5.2. Augmented Reality Enables Mobility

AR enables the visualization of virtual elements regardless of location. Modern mobile devices such as phones and tablets provide support to experience WebXR applications. Therefore, AR-based training enables the trainee to visualize the robot workspace and safety areas in any environment at any time. Besides that, the touch user interface (TUI) provides an easy-to-learn element for interacting with the robot. For this reason, the added value of AR for remote robotics training is the independence of device, time, and location. DTs provide a way to visualize and validate designed trajectories utilizing real hardware, enabling almost hands-on experience for the trainee at a reduced cost and simplified logistics.

5.3. Virtual Reality Enables Risk-Free Safety Training

VR provides an immersive and risk-free method for safety training. Safety perimeters and sensing elements of safety devices, such as laser beams not visible in the real world, can be visualized in VE. Exposing invisible safety features to the trainee enables a clear understanding of areas to be avoided during the robot operation. The added value in VR safety training is the possibility to visually inspect elements invisible in reality and a risk-free way of exercising collaboration with industrial robots. In addition, VR reduces restrictions related to safety regulations by not exposing trainees to hazardous situations commonly found in industrial environments. The added value of the DT is that the training utilizes real-world data from the physical twin, providing a more realistic virtual experience to the trainee compared to a simulated environment.

5.4. Towards Metaverse and Aquatic Environment

DTs and VEs proposed in this paper can be utilized as core elements for Metaverse training environments in the future. The multi-user nature of the Metaverse enables social interaction between trainees and trainers of the VEs, bringing the training experience closer to training in physical environments. Furthermore, the Metaverse converges digital-natives natural with virtual environments with digital industrial training platforms. We intend also to add a virtual aquatic environment based on the northern part of Biscayne Bay, Florida, USA, to demonstrate the generalization of the proposed virtual framework. The range of robot types will expand to include underwater robots and unmanned surface vehicles. One of the primary purposes of such a virtual environment is to provide tools for testing and validating underwater robot navigation algorithms and persistent monitoring of aquatic ecosystems.

6. Conclusions

Digital twin-based VEs for realistic robotic training were proposed in this paper. To the best of our knowledge, the full capacity of DTs with a true bidirectional information transfer has not been fully utilized in robotics training before. Extensively implemented DTs, integrated into training, enable trainees to interact with real hardware and experience the near hands-on sensation of controlling a robot. In conclusion, the added value of XR in robotics training is multifaceted.

AV enables the immersive teleoperation of robotic systems by augmenting interactable physical objects into the virtual world. In addition, AR supports mobility, enabling robotics training anywhere, anytime, with any device. Furthermore, VR introduces immersive, risk-free safety training for robotic applications, relaxing constraints related to safety regulations. In conclusion, cyberspaces not bound by limitations of reality, such as the physical locations of the trainee, trainer, or robot, provide a natural way for the digital-native generation to embrace robotics.

In future work, we intend to add a multi-user capability to enable natural collaboration and social interaction for the digital-native generation. An accessible multi-user training environment enables a trivial way to experience the Metaverse, in aquatic and nonaquatic robotic training.

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