Immersive Virtual Reality for Virtual and Digital Twins: A Literature Review to Identify State Of The Art and Perspectives

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Abstract

Digital twins are a promising technology for various application scenarios such as industry 4.0, medical applications or even urban planning. However, the representation and interaction is often complex and not intuitive. The use of virtual reality in the representation and interaction with digital twins can remedy this. In this paper, we survey the existing literature using the PRISMA guidelines to give a first overview of existing application scenarios, advantages, difficulties and also possible prospects for future work. We identified 30 relevant papers demonstrating first prototypes of combining digital twins with virtual reality. Most applications were in the field of industry 4.0. Popular use cases are remote operations, collaborations, or training and education. While many advantages are presented, also challenges such as VR interaction design, networking optimization, and optimized hardware controls open up also interesting future research fields.

Keywords: Virtual reality, literature review, digital twins, immersion

Index Terms: Computing methodologies—Computer graphics—Graphics systems and interfaces—Mixed / augmented reality; Computer systems organization—Embedded and cyber-physical systems; General and reference—Document types—Surveys and overviews

1 Introduction

In recent years, there has been a growing interest in digital twins (DT) across the industry and academia. Digital twins are described as virtual counterparts to physical entities [19, 25] and facilitate many beneficial use cases that allow cost-effective, user-friendly, and safe scenarios.

Digital twins have often been used in industry 4.0 applications, and it has been shown that digital twins are frequently used and researched, especially in the field of manufacturing [11, 25]. However, there are also several examples of digital twins in various application areas. Enders and Hossbach [11] present a literature review of 87 digital twin applications and also emphasize that most digital twins are used in manufacturing. Still, the potential application scenarios are diverse and include aerospace, energy, automotive, marine, petroleum, agriculture, healthcare, and the public sector. The three primary purposes of digital twins were described as simulation, monitoring, and control. In recent years, many authors have presented the potential of digital twins in various fields through literature reviews. In a study in 2020 [19], the authors present a collection of 92 papers related to digital twins to identify characterization features.

A major gap was identified in many of the presented papers: the realization of appropriate visualization of interaction forms. And one technology that was often cited as a key technology for the future of digital twins to overcome these issues and strengthen the visualization capabilities of digital twins is virtual realities (VR) [10, 37, 41].

With the advent of consumer-oriented virtual reality technologies such as the Oculus Rift or the HTC Vive - which are less expensive and more accessible - the design, research, and development of virtual reality experiences for experiences outside of entertainment has reached a new peak for many fields such as industry 4.0, education, tourism, or health (see literature reviews [8, 13, 53]).

While many literature reviews have been presented to describe the potential and application of digital twins in general, there is not yet a literature overview focusing on identifying the potential of virtual reality for digital twins. Therefore, in this paper, we present a literature review based on the PRISMA guidelines to give an overview of the state of the art, focusing on answering the following questions:

- *RQ1* How relevant is the topic of digital twins implemented with VR in relation to the number of research publications?
- *RQ2* What are the main application fields for VR-based digital twins?
- *RQ3* What are the described use cases of digital twins using VR?
- *RQ4* What technologies were used for experiencing the VR experiences, but also for developing them?
- *RQ5* What are the issues and problems described when combining VR and DT?

2 Method

In this study, the primary goal was to identify relevant literature describing the use of (fully immersive) virtual reality experiences for various digital twin applications to find out more about the application fields, use cases, benefits, and issues, and to describe the state of the art with a focus on future research opportunities. To this end, we conducted a literature search following the PRISMA [31] guidelines and focused on the ACM Digital Library, Scopus, and IEEE Xplore databases. As inclusion criteria, we defined that the paper must be written in English and must be from a peer-reviewed journal or conference.

2.1 Search Criteria

To collect literature in the Identification phase, we used the following search string: *("virtual reality" OR "VR") AND ("digital twin" OR "virtual twin")*. The search was conducted in May 2021. We identified 515 papers (see also Figure 1). During the Screening and Identification process, we removed 435 papers as they did not meet the inclusion criteria or were identified as duplicates. We read the full texts during the Eligibility phase and removed 50 papers because of the missing focus on immersive VR or DTs. Papers

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Table 1: Overview of search criteria

Searching Index	Content
Databases	ACM, IEEE Xplore, ScienceDirect
Search String	*("virtual reality" OR "VR") AND ("digital twin" OR "virtual twin")*
Type	Articles, Conference Papers (in English)
Search Time	May 2021

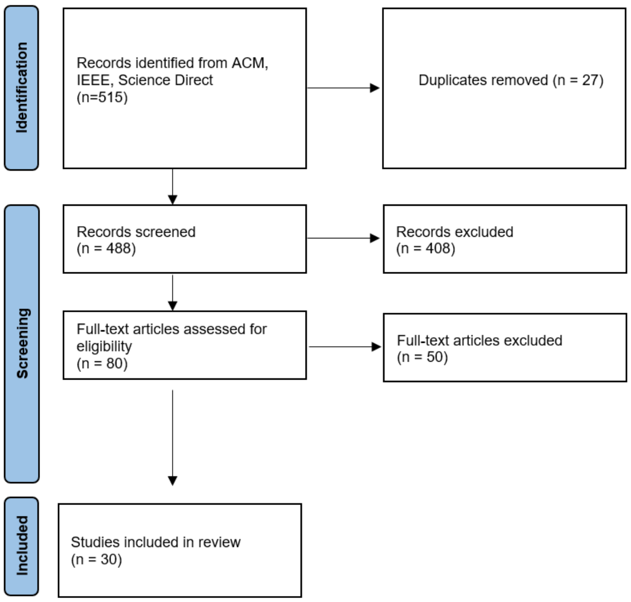

Figure 1: PRISMA guidelines diagram

describing only ideas and concepts without first implementations, demonstrating ideas, and conceptual framework descriptions have also been excluded. The final corpus includes 30 publications. Table 1 summarizes the relevant search criteria.

2.2 Categorization Criteria

We used the publication year, the applications fields, described use cases, and the used technology to categorize the papers.

3 Results

Our final corpus for this review includes 30 papers introducing the concept of virtual reality for digital twins. Figure 2 illustrated an overview of the number of publications per year. No relevant publications were identified before 2018, which might be due to the novelty of digital twins and the introduction of consumer-oriented VR technologies. It should be noted that the search was conducted in May 2021, which might lead to a lower number of publications in 2021.

3.1 Application Fields

In their literature review on digital twins, Enders and Hossbach [11] identified applications in the following domains: manufacturing, aerospace, energy, automotive, marine, petroleum, agricultural, healthcare, and the public sector. When we analyzed the VR applications, we saw similar patterns. Most of the applications were in the field of manufacturing. We categorized them as industry 4.0 applications. While training and education can be described as a use case for different application fields, many publications specifically described experiences designed for the educational sector. As a result, we added training and education as a separate application field (and later as a use case). Robotics can also be found in industry 4.0 or also health. Still, we used it as a separate application field, as some digital twins were explicitly designed to design and study robotic behavior (e.g. drones) and did not describe a detailed application field. Two digital twins were identified in the area of automotive. And one experience each in the fields of health, gastronomy, urban, BIM, aerospace, and astronomy. Table 2 links the references to the described application fields.

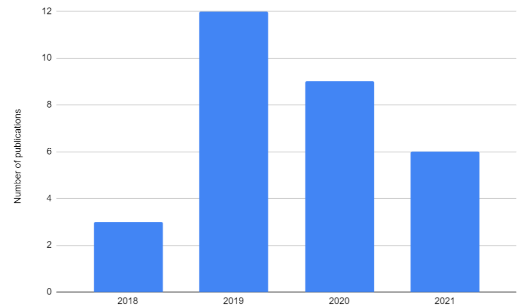

Figure 2: Number of publications per year (as of May 2021)

Table 2: Overview of references linked to application fields

Domain	**Reference**
Industry 4.0	[1,6,12,14,21,23,27,30,33, 35,38,42,47,50,52]
Training, Education	[16,32,39,45]
Robotics	[20,29,51]
Automotive	[9,48]
Health	[26]
Gastronomy	[22]
Urban & Infrastructure	[18]
Aerospace	[44]
BIM	[40]
Astronomy	[2]

In the following, we describe these application fields with examples from the literature.

Industry 4.0

Similar to the general literature on digital twins, most of the identified applications in the literature on digital twins with VR focus on Industry 4.0. Very often, manufacturing examples are shown. In [47], the authors describe a DT system developed based on VR as a replica of a human-robot welding environment. In this example, the experience is designed to engage human users in interacting with the welding scene. In [52] the authors propose an architecture (conceptualization + proof of concept) for integrating real-time bidirectional data in the context of Virtual Factory (VF). The system also allows for multi-user remote collaboration (real-time). In [12], the authors propose a digital twin with a VR view to help industries to prepare virtual assets and configure process scenarios from virtual models (opening the possibilities for real-time, remote cooperation). In [14], the authors present a methodology for improving the decision-making process in the activity of planning shop floor layout in the context of Industry 4.0. In the tool, the stakeholders collaborate in a virtual reality setting, which is evaluated in an industrial use case. The VR allowed groups to find better and more ergonomic and sage solutions. In [17], the authors describe the use of a digital twin of an RFID-measuring-chamber in VR for the primary purpose of education. They discuss the benefits of this environment that most of the logistical problems inherent to lab-based learning can be overcome through virtualization and remote-controlled labs.

Training and Education

While training and education can also be seen as a use case for various domains (e.g. training for Industry 4.0 applications), several publications focused on creating experiences for the educational fields e.g. by developing virtual educational laboratories.

In [32], the authors investigate the use of VR technology in emergency staff training. To do this, they tested the system by replicating the environment (and eventual emergency) with a realistic scenario. They found that the training produced more timely/efficient and less stressful reactions in emergency situations. Moreover, this enables the identification of problems in the procedure, and its re-design, when needed. Furthermore, the data can be uploaded to the digital twin to create new training scenarios when an emergency occurs. In [45], the authors develop a novel framework to generate coherent context-realistic training simulators from data collected from actual construction projects to enhance construction training simulators. Their (reduced) use case study focuses on safety and teamwork.

Automotive, Engineering, Robotics

In [38], the authors present a real-time optimization method to optimize the production process via VR, in which the user can interact with a simulation model (i.e., digital twin) of the production system. In [9], the authors analyzed the use of digital twins in VR for product assembly. The virtual scene is designed to simulate a real assembly environment where a robotic arm is used, and its real counterpart is placed in a laboratory. In [35], the authors use a virtual reality digital twin in environments where robots and humans collaborate. Wherever humans and industrial robots share a common workplace, accidents are likely to happen and always unpredictable. Therefore, their goal is to understand human reactions to both predictable and unpredictable robot motions and thus exploit VR digital twins to develop collaboration strategies.

Urban and Infrastructure

In [18], the authors develop a virtual (or digital) twin of an underground opening. They test the simulation by asking participants to identify the possible causes of failure and experiment with several support measures. The virtual reality setting allowed safe training focused on situational awareness, as it provided a visual detection of ground control problems, geological structures, and instabilities. The decision-making process can be enhanced by understanding the effect of different support measures and evaluating the results of their choices. This can also be used in educational scenarios.

Building Information Modeling (BIM)

In [40], the authors apply the concept of digital twins and virtual reality to the problem of monitoring indoor thermal comfort cost-effectively. They present a framework that integrates real-time data from sensors and re-create the environment in VR to enable a better and more user-friendly visualization while also allowing a real-time modification of the sensors' parameters.

Astronomy

In [3], the authors describe a comprehensive reality framework of the digital twin of the Austral Square Kilometre Array Pathfinder (radio telescope array). They use realistic and engaging visualizations of the ASKAP to support the understanding of the system of various users such as instrument operators, scientists, the general public, and decision-makers. The immersive character of large-scale VR systems allows (e.g. EPICentre system) an optimal resolution, immersion, and visual experience and will enable users to understand the scale of this telescope.

Health

In general, digital twin literature also the field of health and healthcare was described often. Also, combined with virtual reality experiences, many relevant options can be imagined. In [26], the authors present a digital twin supporting remote surgeries.

Gastronomy

In [22], the authors describe the use of a digital twin in combination with VR to visualize and interact with an ice cream machine.

Aerospace

In [44], the authors describe the use of virtual reality to visualize the performance of a fleet of an aircraft engine and use a combination of the Oculus Rift and Leap Motion technology to facilitate the interaction.

3.2 Use Cases

In the literature, various use cases have been identified. While the majority facilitates remote operation and controlling, also ideas to use these digital twins for remote collaboration, training, or evaluation methods have been identified.

Several advantages have been shown when combining digital twins with VR. This includes the following aspects: low-cost [30], advanced visualization in immersive 3D spaces [1,47], natural and direct interaction forms [47], advanced controlling and data collection options [47], portability [30], remote usable [1, 29], scalability [30], augmented use (e.g. additional information) [22], real-time [29].

Evaluation and User Studies

Digital twins can provide a safe environment to assess behaviors and processes. In [49], the authors present a digital twin of the highway virtualizing of real-time traffic information. This would be designed to enhance the driving experience with augmented reality glasses. To evaluate the scenario and the augmented reality system, they introduce a VR experience to assess the driver behavior during a take-over-request in automated vehicles. Also, to collect and compare data from different users (e.g. expert users vs. novice users), [47] a combination of VR and DT has been shown as a valuable option.

Remote Operation

Remote operation applications allow users to operate complex machines and mechanical systems remotely. However, the interaction with remote interfaces and the visualization of the results is often an issue of remote operations. Virtual reality environments can offer a more natural and intuitive interaction and visualization form. In [7], the authors describe the development of a VR representation of a Fanuc Roboshot Injection Moulding a-S130ia and point out different challenges such as interaction, evaluation, and network issues, which are described closer in a later section of this article. They propose an integrated framework to measure the user's quality of experience through capturing physiological metrics, heart rate, and eye-tracking data while interacting with the environment. Another example of remote operation outside the Industry 4.0 domain was presented by [26]. The authors present a digital twin system supporting a remote surgery, combining a VR experience and the interaction with a robotic arm.

Remote Collaboration and Guidance

Many traditional digital collaboration tools split the "person space" (verbal and nonverbal cues) and the "task space" (space where they work together) as described by Buxton [5], which often leads to misunderstandings, errors, and delays. Environments that allow direct communication when working together (e.g. physical pointing on parts of an object) are faster and more productive [15]. Virtual reality environments support a space that allows co-located collaboration and communication. Ladwig et al. [28] describe in their work how a local worker can work together with a remote worker using a virtual reality twin. The local worker receives hints and guidance from the remote worker through inexpensive installed blinking LEDs. They showed a significantly shorter completion time and fewer errors when comparing this method with traditional voice guidance.

In [42], the authors explore Singapore's panorama in terms of industry usage of VR solutions. One of the examples that they report shows how digital twins and VR can be extremely useful in social distancing situations (i.e., Covid19). For instance, the VRcollab LITE platform allows project teams to work collaboratively despite being remote. The members of the teams are immersed in an environment that is the digital twin of the real one. They surveyed team members in 3 scenarios/groups, and they benefited from increased teams' efficiency, reduced workforce, and time saved.

Digital Twins in VR as an Educational and Training Tool

Digital twins in VR can be a great tool to educate different users group about complex systems. In [3], the authors present a digital twin of a radio telescope and point out the potential of the immersive and visual experiences of VR to help users obtain an understanding of the *"scale of the telescopes and the surrounding geography of the observatory as well as the temporal progression."* Portable VR solutions are described as a great tool supporting outreach. In [17], the authors show the potential of digital laboratories (a digital twin of an RFID-Measuring-Chamber) for lab-based learning. It reduced the disadvantages of pure virtual experiences and added benefits of virtualization and remote-controlled labs.

Digital Twins in VR to support Understanding and Decision-Making

In [14], the authors create digital twin combined VR while planning a shop floor layout. In a collaborative setting, decision-makers are invited to understand the current situation better and find new solutions.

Corner Case: VR as an Authoring and Design Tool

The spatial and three-dimensional interaction in VR makes it a relevant tool to display digital twin environments and author and configure them. In [36], the authors introduce the tool "Corsican Twin" to enable the creation of augmented reality data visualizations in VR using a digital twin. Their paper describes three main use cases: on-site equipment debugging and diagnosis, remote incident playback, and operations simulations for future buildings.

3.3 Technologies and Interaction Forms

Most authors mentioned that they used the HTC Vive as a head-mounted display (HMD) or the Oculus Rift for the VR experience (see Figure 3). New publications also mentioned using the Oculus Quest, which allows a cable-free experience. Only one publication mentioned using a mobile VR solution with a Google cardboard. As a development tool, five publications added that they had used Unity, one used the Cry Engine.

Interestingly, several authors also mentioned the use of additional hardware such as the introduction of gloves or the Leap motion to enhance the interaction with the VR experience or setups to enable a closer look-and-feel experience with the digital twins or added additional information to the physical twin to map the interaction in the VR experience. In [28], for instance, the authors used the HTC Vive Pro and developed the experience in Unity. On the real machine, LEDs were installed and reacted on user input in the virtual environment. The VR user pointed out parts of the virtual machine, and as a result, the LEDs started to blink on the real machine.

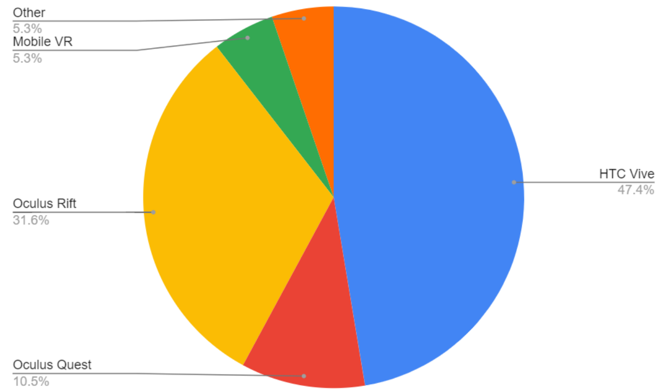

Figure 3: Overview of used HMDs (when information available)

3.4 Challenges and Issues

The following main challenges have been identified: cybersickness [7], acceptance of VR technology [7], cables [44], evaluating experiences [7], network challenges and communication, traffic [7, 26, 47], cybersecurity [26], and hardware to control [51].

In [7], the authors summarize key challenges for VR-based teleoperation systems. The main challenges include the VR interaction design and natural controls to avoid cybersickness, issues of acceptance, and visual fatigue. Another issue to note is missing possibilities to evaluate the quality of experience. They propose a framework including biometrics measures and eye-tracking to improve the experience. Additionally, they point out the requirement of comprehensive networked capabilities.

4 Discussion

With respect to (RQ1), we found that, especially since 2018, there has been a high interest in virtual reality in the field of digital twins. Also, when combining our literature review with the general literature review on digital twins e.g. by [11, 19], who identified in 2019 87 relevant publications and 2020 92 papers, we can see that identifying 30 relevant papers combining VR with digital twins in 2021 could be interpreted as a relatively high number. It should be noted that many papers have been excluded as they were only presenting concepts to extend the digital twin experience to a VR environment (e.g. in [43]). This has often been described as a possible extension of the current implementation when three-dimensional representations have already been implemented (e.g., CAD or Unity). Thus, we can see a strong interest in the DT community in VR technologies.

For RQ2, we identified various relevant applications fields for digital twins combined with VR. Like the literature reviews focusing on digital twins, the main area is industry 4.0. However, the potential for use cases in various other application fields is visible. In this paper, we see different use cases showing the potential for fields such as health, automotive, BIM, education, or even gastronomy.

For RQ3, we identified similar use cases in the digital twin literature such as remote operation, remote collaboration, guidance, training, or decision-making. However, the usage as an evaluation tool and to provide a safe space for user studies was a new finding. An exciting corner case has been found that described how VR could also be used as an authoring or design tool.

For RQ4, we mainly looked at the technologies in terms of hardware, and used development. The most surprising finding for the authors was the strong use of Unity, but no use of the Unreal Engine, as also this technology might support effective integration and visualization of digital twins. In terms of hardware, the HTC Vive was described in most papers. The Oculus Quest was also noted in newer publications, which might be a relevant hardware for future developments, as it reduces accessibility issues and problems around cable management. However, it also comes with limited performance without a connection to a PC. Several identified use cases have incorporated their own hardware solution to control the digital twins (e.g. a specific glove in [51]). A future challenge will involve standardization of hardware to maintain digital twin solutions in a user-friendly way.

Similar problems and challenges were described in many publications (RQ5). We can categorize them in VR usability (such as cable management, cybersickness, or interaction design), missing hardware (such as missing standardized equipment to control the twins), and communication and network challenges (such as traffic speed and cybersecurity).

While many issues have been described, overall, the tone towards using VR in this domain has been positive. The demonstrated examples and many posed ideas are promising and open up many new research strands and application fields for academia and industry.

4.1 Limitations

It is important to note that the term "digital twin" is still relatively young in literature, and in this review, we have focused on works that use this term to present their research. However, there are relevant works in the past that already take up and describe similar concepts without using this term directly, such as [4, 24, 34, 46]. In addition, it must be mentioned that the term digital twin is strongly influenced by industry and that there are many implementations in the industrial sector that, however, do not appear in the academic literature.

4.2 Future Research

With regard to the presented issues and ideas conceptualized in the reviewed papers, the authors propose the following primary future directions to advance this research field: (1) research and development of digital twins in new applications domains, (2) user studies with stakeholders, (3) network and communication improvement (5G), (4) natural interactions between the twins, (5) more research with newer VR HMDs such as the Oculus Quest, which e.g. reduces usability issues around cable management, (6) natural and immersive forms for the visualizations, (7) hardware adaptions to enable interactions between the twins, and (8) data analytics of the user experience to learn from the digital twin to improve the physical twin.

5 Conclusion

In this paper, we reviewed 30 publications demonstrating the potential of virtual reality experience in the context of digital twins to understand better application scenarios and relevant use cases, opportunities and challenges, and the current state of the art. Several studies have shown promising first results and interesting opportunities; however, they also showed that this research strand is still early. Many papers (which were excluded for the literature review) only presented first ideas and concepts. Also, among the 30 included publications, many only presented prototypes or proofs-of-concept, and only a few also presented evaluations with the target group.

The representation of VR digital twin experiences is similar to digital twin research and strongly focuses on fields related to Industry 4.0 applications. Only a few publications also showed the potential for health, education, urban, automotive, or even gastronomy.

The primary use cases have been described as an intuitive form of remote operation, remote collaboration or guidance, training, collecting data, and performing user studies.

The main benefits were described as a lost-cost solution, the possibility of supporting advanced immersive (and augmented) visualizations, enabling natural and direct interaction, advancing the controlling and data collection, enabling a flexible and portable experience, and allowing remote work.

However, also several challenges have been identified. This includes challenges around the usability of VR (e.g. cybersickness, acceptance of VR technology, cables), network challenges (e.g. communication traffic and security), and additional hardware and devices to make the experience with the digital twin more realistic and easier to use.

Based on the presented review, we can see a strong interest in advancing the connection between digital twins and virtual reality and opening up many open research directions.

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