SCHOOL OF COMPUTATION,
INFORMATION AND TECHNOLOGY —
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TECHNISCHE UNIVERSITÄT MÜNCHEN

Master's Thesis in Informatics

Impact of Immersion and Presence on Learning during Virtual Training Processes

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Einfluss von Immersion und Präsenz auf den Lernerfolg virtueller Trainings

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I confirm that this master's thesis is my own work and I have documented all sources and material used.

Munich, 15.06.2023 Mert Ülker

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Abstract

Training processes have a pivotal role for many businesses in helping them sustain uninterrupted operation. They are utilized not only to keep the employees on an adequate level of competencies, but also to support them in acquiring new skills and adopting novel methods. Organizations in many different industries depend on the efficient and effective training processes to ensure that their employees perform their tasks proficiently. While onsite training processes have been employed for this mission traditionally, virtual training has emerged with the advent of technology as an innovative approach addressing the limitations of their onsite counterpart. These type of training processes allow remote participation of individuals and eliminate the need for physical presence. With the increasing prevalence of remote work in particular, virtual training continues to become more relevant. In order to deliver content remotely, many organizations invest in frequently adopted virtual training processes such as webinars and e-learning courses that leverage digital platforms. Although their benefits are significant especially in domains with limited resources, they also suffer from a major drawback in comparison to onsite training. Due to the lack of physical presence, trainees participating in this type of training processes commonly suffer from low engagement, which in turn leads to suboptimal learning outcomes. Traditional virtual training processes adopt different strategies, focusing primarily on interactive elements to eliminate the adverse effects of low engagement on the learning outcome. Even though they establish relative success with regards to passive forms of instruction, the level of engagement offered by in-person training is still unmatched in most cases. In this thesis, we focus on the immersion and presence aspects of virtual training processes in order to realize high levels of engagement during training, in turn leading to positive effects on learning. We propose a virtual training process, comprising multiple versions with varying levels of immersion that utilize a Virtual Reality (VR) foundation, supplementary sensory feedback and a set of Augmented Virtuality (AV) techniques. We perform evaluations on the implemented process and propose future work to acquire further insights on the effect of immersion on the learning outcome during virtual training processes.

Kurzfassung

Trainingsprozesse spielen für viele Unternehmen eine zentrale Rolle bei der Aufrechterhaltung eines ununterbrochenen Betriebs. Sie werden nicht nur genutzt, um die Mitarbeiter auf einem angemessenen Kompetenzniveau zu halten, sondern auch, um sie beim Erwerb neuer Fähigkeiten und bei der Übernahme neuer Methoden zu unterstützen. Organisationen in vielen verschiedenen Branchen sind auf effiziente und effektive Trainingsprozesse angewiesen, um sicherzustellen, dass ihre Mitarbeiter ihre Aufgaben kompetent ausführen. Während für diese Aufgabe traditionell Trainingsprozesse vor Ort eingesetzt wurden, hat sich das virtuelle Training mit dem Aufkommen der Technologie als innovativer Ansatz offenbart, der die Beschränkungen ihres Gegenstücks vor Ort angeht. Diese Art von Trainingsprozessen ermöglicht die Teilnahme von Einzelpersonen aus der Ferne und macht die physische Anwesenheit überflüssig. Vor allem mit der zunehmenden Verbreitung von Telearbeit gewinnt das virtuelle Training immer mehr an Bedeutung. Um Inhalte aus der Ferne vermitteln zu können, investieren viele Unternehmen in häufig eingesetzte virtuelle Trainingsprozesse wie Webinare und E-Learning-Kurse, die digitale Plattformen nutzen. Obwohl ihre Vorteile vor allem in Bereichen mit begrenzten Ressourcen beträchtlich sind, haben sie allerdings im Vergleich zu Trainings vor Ort einen großen Nachteil. Aufgrund der fehlenden physischen Präsenz leiden Teilnehmer bei dieser Art von Trainingsprozessen in der Regel unter einem geringen Engagement, was wiederum zu suboptimalen Lernergebnissen führt. Traditionelle virtuelle Trainingsprozesse verfolgen andere Strategien und konzentrieren sich in erster Linie auf interaktive Elemente, um die negativen Auswirkungen des geringen Engagements auf das Lernergebnis zu beseitigen. Auch wenn sie im Vergleich zu passiven Unterrichtsformen relativ erfolgreich sind, bleibt der Grad des Engagements, den das persönliche Training bietet, in den meisten Fällen unerreicht. In dieser Arbeit konzentrieren wir uns auf die Immersions- und Präsenzaspekte virtueller Trainingsprozesse, um ein hohes Maß an Engagement während des Trainings zu erreichen, was wiederum zu positiven Effekten auf das Lernen führt. Wir schlagen einen virtuellen Trainingsprozess vor, der mehrere Versionen mit unterschiedlichen Immersionsgraden umfasst, die eine VR-Basis, zusätzliches sensorisches Feedback und eine Reihe von AV-Techniken nutzen. Wir führen Evaluierungen des implementierten Prozesses durch und schlagen zukünftige Arbeiten vor, um weitere Erkenntnisse über die Auswirkungen der Immersion auf das Lernergebnis während virtueller Trainingsprozesse zu gewinnen.

Contents

Acknowledgments **iii**

Abstract **v**

Kurzfassung **vii**

1. Introduction **1**

2. Related Work **5**
2.1. Immersion and Presence 5
2.2. Virtual Training 6
2.3. Virtual Reality Training 7
2.3.1. Haptic Feedback in VR Training 10
2.3.2. Olfactory Feedback in VR Training 10
2.4. Augmented Virtuality 11
2.5. Object Tracking 14
2.6. Digital Twin 15

3. Research Evolution **19**
3.1. Research Vision 19
3.2. Initial Experiments 23
3.3. Design Changes and Adaptations 29

4. Implementation **35**
4.1. Base VR Level 35
4.2. Haptic VR Level 39
4.3. Augmented Virtuality Level 41

5. Evaluation **45**
5.1. Setting 45
5.2. Participants 46
5.3. Questionnaires 46
5.4. Results 48

6. Future Work **57**

7. Conclusion **61**

A. Immersion Review 63

B. Education and Training Olfactory Interfaces 65

Abbreviations 69

List of Figures 71

List of Tables 73

Bibliography 75

Online References 81

Other References 83

1. Introduction

In many industries, training plays a crucial role in facilitating seamless operation of businesses through giving individuals a platform to acquire new knowledge, develop required skills and learn operational techniques, in turn ensuring their proficiency in performing their tasks efficiently. Moreover, they allow the trainees to improve on their existing operational capabilities by helping them adopt new expertise. Companies across a wide variety of industries invest in training programs with the goal of ensuring employee competency within their field. With support of training processes, these organizations can push employees to improve their existing abilities in order to keep up with the evolving demands of their respective industries. As they expand operations through the integration of novel systems, hiring of new employees or adoption of additional tools, the need for training increases. For many of these organizations, it is essential to ensure efficient training of employees for adapting to new set of tools, methods and dynamic work environments in general, particularly in rapidly evolving industries.

Traditionally, onsite training sessions such as seminars and workshops have been the main methods of equipping individuals with new knowledge. However, the advent of technology and digitalization gave rise to virtual training emerging as an innovative approach to overcome the limitations associated with in-person training. By allowing individuals to engage remotely and eliminating the need for physical presence, many drawbacks of onsite training are overcome. The drawbacks such as dependency on limited physical resources and the need to develop detailed plans for their time allocation become irrelevant due to the remote nature of virtual training, along with the flexibility it offers. By adopting virtual training, organizations allow their employees to perform a variety types training such as on-boarding, soft skills and product training from potentially anywhere on the world at any given time. Particularly in light of the COVID-19 pandemic and the rise of remote work, the time and location flexibility of training stopped being only an advantage, but rather became a necessity. For many organizations in a wide range of industries, virtual training is no longer a commodity but a requirement due the nature of their operations.

In order to address the requirements of the modern times and benefit from the advantages of virtual training, organizations invest in different kinds of virtual training processes that leverage digital platforms to deliver content remotely. Common types of virtual training are video-based training which involves the use of pre-recorded material to deliver training content, webinars which consist of instructor-led live presentations or workshops conducted over the internet, and e-learning courses that consist of multimedia elements and accompanying tests. While these traditional types of virtual training processes have been widely adopted in many industries due to their benefits and capabilities in addressing the requirements of our age, they still represent certain disadvantages.

Despite the advantages they offer, commonly used virtual training processes face specific challenges that hinder their effectiveness in achieving desired learning outcomes. Even though the traditional virtual training methods of webinars, e-learning and video-based training processes have provided accessibility and flexibility, they commonly suffer from low engagement and focus in comparison to onsite training processes. In most instances, the lack of physical presence and interaction of these methods can potentially lead to a reduction in the involvement, attention and motivation of the trainee performing the virtual training process, in turn undermining the efficacy of the training process and leading to suboptimal learning outcomes. The potential negative effects on the learning outcome caused by this drawback of commonly used virtual training methods consist of slower learning process, lowered accuracy of acquired knowledge and reduction in knowledge retention periods.

Various strategies have been adopted by traditional virtual training processes for the purpose of addressing these challenges and mitigating the caused negative effects on the learning outcome. These strategies primarily focused on establishing higher engagement of the trainee through the utilization of more interactive elements that encourage active participation, and gamification techniques such as leaderboards or achievements that are aimed to increase motivation. Furthermore, these traditional virtual training methods have been used in combination to leverage their individual strengths and maximize the benefit on user engagement. While these strategies demonstrate success compared to passive forms of instruction, in most cases they still fail to match the level of engagement that onsite training processes offer.

In this study, we focus on the improvements on feelings of immersion and presence, and their impact on the learning outcome during a virtual training process. We review past work with an emphasis on immersive virtual training processes and propose our own virtual training tool comprised of varying levels of immersion. We build these different levels through the utilization of a VR foundation, supplementary haptic feedback and set of AV techniques. During the design and implementation of the proposed tool, we maintain a focus on distancing from passive forms of instruction. We prioritize interactivity and freedom, allowing trainees of the process to make mistakes, obtain instant feedback and experience potential results of actions first-hand. With our work, we aim to realize an immersive virtual training process that leads to higher engagement relative to traditional virtual processes, in turn positively affecting the learning outcome. Furthermore, we evaluate our implemented virtual training tool and assess its perceived usability, potential on learning and accuracy of transmitted knowledge.

In the following, we start with the presentation of related work on topics closely related to our research. After the review of past work, we present our complete research process beginning with our initial design idea for the proposed virtual training tool. Subsequently, we report on our experiments for assessing the suitability and feasibility of certain initial design aspects. We follow the experiment report with the adaptations and changes made on the design based on the assessments and continue with a detailed presentation of the proposed tool's implementation, where we introduce the varying individual versions of the tool defined as immersion levels. Following the presentation of individual versions of our tool, we review the performed evaluation of the proposed virtual training process and analyse the results of our user study. Finally, we propose future work for potential improvements and conclude our research.

2. Related Work

In this chapter, we will introduce the concepts frequently addressed within this thesis and review some of the research on these topics. We will start with the concepts of immersion and presence, followed by a presentation of the topic of virtual training. We will subsequently go into further detail with virtual reality training and review two of the feedback types potentially employed in virtual reality training, namely haptic and olfactory feedback. Finally, we will introduce the topics of augmented virtuality and tracking consecutively.

2.1. Immersion and Presence

Immersion and presence are two concepts frequently discussed in research focused on or related to virtual environments. While some past work use these terms interchangeably, others propose their distinct definitions for each of these concepts and differentiate between them, while still acknowledging their relation with one another. In this section we present definitions of immersion and presence by referencing previous literature and review some of their characteristics.

One of the earliest studies done related to both concepts of immersion and presence is by Slater and Wilbur (1997). In their work, they distinguish between the two concepts and define immersion as a description of a technology that describes the capability of computer displays on delivering an inclusive, extensive, surrounding and vivid illusion of reality to the senses of human participants. Subsequently, they highlight that immersion can be an objective and quantifiable description of what a specific system offers, and define presence as a state of consciousness and sense of being in the virtual environment [SW97]. While later research follows their definitions of immersion, others adopt varying definitions or propose their own. In their research, Nilsson et al. (2016) present a comprehensive review of some of these definitions as seen Appendix Table A.

Further research on presence follows Slater and Wilbur's conceptualization of immersion as an objective property of the technology, and presence as a psychological reaction to this technological property [Cal14]. IJsselsteijn (2004) presents immersion as a term used to describe a set of physical properties of the media technology that may give rise to presence [IJs04] while Rettie (2004) defines presence as a subjective experience that is promoted by immersive environments [Ret04]. In their study, Van Den Hoogen et al. (2009) also summarize that technology can be immersive but whether a person experiences presence is subjective [VID09]. In another work, Mestre (2006) defines immersion as a technology related objective aspect of virtual environment, whereas presence is a psychological, perceptual and cognitive consequence of immersion [Mes+06].

According to Mcmahan (2003), three conditions create a sense of immersion in a virtual reality or 3-D computer game [Mcm03]:

1. The user's expectations of the game or environment must match the environment's conventions fairly closely.
2. The user's actions must have a non-trivial impact on the environment.
3. The conventions of the world must be consistent, even if they don't match those of physical world. [RCD97] [She00]

2.2. Virtual Training

In this section, we provide a brief review of the some research conducted on the topic of virtual training as an intermediary step towards more immersive training processes, including virtual reality training.

In one study based on traditional virtual training processes, Zhang et al. (2006) focus on the e-learning and aim to assess the impact of interactivity on learning effectiveness. In order to generate a thorough analysis, they conduct an empirical study with three different e-learning environments and an additional onsite classroom environment. They differentiate between their e-learning tools by incorporating one with an interactive video, another with a non-interactive video, and maintaining the last variant as a foundational level no videos incorporated. As a result of their study, they determine that the test group performing the training with the interactive video achieved significantly better learning performance compared to other groups, depciting the positive effects of interactivity on the virtual training process [Zha+06].

Other studies have been made with less traditional and more engaging virtual training processes with the intention of learning the effects of the dissimilarities of varying systems on the learning outcome. During their study, Terlaak et al. (2015) investigate the use of three different virtual training methods with the primary goal of identifying their learning effects. They focus on the training scenario of myosignals and adopt different feedback mechanisms on varying versions of the virtual learning process. While the first variant represents a basic tool which only utilizes a computer screen for myosignal feedback, the second variant is equipped with a virtual myoelectric prosthetic hand and a computer game is employed as the final variant. Despite performing training with versions of the tool with varying feedback mechanisms, their results show no significant differences in learning effects [Ter+15].

2.3. Virtual Reality Training

The topic of virtual reality in training and education has been researched considerably throughout last couple of decades as the VR technologies themselves have been further advanced over the years and improved on their capabilities. In an earlier study, Kozak et al. (1993) concluded that the learnings from virtual reality training did not transfer to the real-world tasks as a result of their research. Although the learnings of subjects during VR training was specific only to the context of virtual reality in their setting, they still argue that many of the their barriers to transfer are due to the technological state-of-the-art and indicate that the promise of VR training is especially significant [Koz+93]. On another early research, Psotka et al. (1995), focus on immersion as the key added value of VR while analyzing what cognitive variables are connected to immersion [Pso95]. During their research, they also highlight the definition of immersion, its benefits and ways to generate it in synthetic environments. They conclude that the research and development of VR technology for the purposes of training has many potential high-payoff areas and that it should be further developed as an integral part of educational and training processes in parallel to other tools.

On more recent work, Carruth et al. (2017) and Xie et al. (2021) review the traditional training processes and highlight the limitations they represent. These include the potential time and money costs of real-world training setups, unappealingness/unintuitiveness of theses processes due to lack of visual hints and impossibility to train some skills in the real world that can be only safely trained in simulators [Xie+21]. Their research also draws attention to the fact that some real-world training options may only be available at specific times (e.g. seasonal conditions) and that sometimes it may be impossible to perform real-world training because it may involve work spaces or tasks that are still being designed or environments that cannot be recreated [Car17]. With their research they argue that VR has the potential to provide solutions to many of these limitations and that its application to education and training has been demonstrated in many domains.

In their research, Pantelidis et al. (2009) give some reasons to use VR in education which also translate well into the training scenarios. These reasons include the ability to utilize new forms and methods of visualization, which may lead to more accurate illustrations and new perspectives with additional value. The authors also list students' motivation for VR and argue that it encourages active participation rather than passivity, or in other words, it leads to higher engagement. Another reason listed is the fact that VR allows the learner to proceed through an experience during a broad time period not fixed by a schedule, at their own pace. While the authors highlight the advantages of using VR for teaching purposes, such as increased motivation/attention, accurate illustration of features/processes and encouragement of active participation, they also draw attention to some disadvantages. These include cost/time necessary for learning how to use hardware and software, potential health and safety effects, and possible reluctance to use and integrate new technology into an established workflow. However, they also argue that these issues may fade as virtual reality becomes more commonly used [Pan09].

On other studies, Velev et al. (2017) highlight the importance of emulating the human perception process while creating a virtual environment and argue that the major senses have to be stimulated, including an awareness of where the user is within the environment, to get a perfect feeling of immersion. While they draw attention to similar advantages as previously mentioned, they also state some weaknesses of VR. They express that VR is often not taken seriously and that trainees can show attitude which assists for winning the game, but not fully engage their mind to acquire new knowledge and critical thinking. They also argue that VR requires high graphic capabilities which may not be possible with standard equipment and that VR solutions often can not be matched with similar environments from different developers since many companies offer their own tools to create these environments which may not be with the rest regarding hardware/software. As a conclusion, they state that VR will require professional skills for content generation, full immersion, interaction, programming and implementation, and that the new generation of VR specialists must be educated for delivering solutions that take these shortcomings to employ VR in education and training [VZ17].

In addition to academic work, a recent tech report published by the consulting company PricewaterhouseCoopers focuses on the effectiveness of VR for soft skills training. The study performed by the group aims to identify whether the utilization of VR for this type of training represents any advantages over traditional onsite or virtual training processes. As a result of their study, they observe a significant confidence increase to act on the training material and much faster training processes compared to both classroom training and e-learn. Furthermore, they identify a four times higher focus of trainees participating in VR training relative to those training with e-learn courses. Following these observations, they conclude that virtual reality training processes have a high potential in ushering a new era of enterprise training through their capabilities of delivering immersive and effective soft skills training experiences. [EM20]

Following is a brief review for types of VR training within the industrial setting, followed by a review of existing research in that context:

- **Safety training:** Adoption of VR for the purpose of training individuals in safety measures and emergency procedures such fire evacuations.
- **Equipment operation:** Adoption of VR for the purpose of training individuals on the operation of new or complex machinery such as teleoperation tools and simulators.
- **Process training:** Adoption of VR for the purpose of training individuals on the newly adopted procedures such as manufacturing processes.

- **Maintenance training:** Adoption of VR for the purpose of training individuals on the predictive maintenance of tools in order to prevent adverse future effects.

- **Soft skills training:** Adoption of VR for the purpose of training individuals on soft skills such as communication, leadership and teamwork.

In their study, Gavish et al. (2013) evaluate the use of both VR and AR platforms for Industrial Maintenance and Assembly (IMA) tasks training and state that these platforms offer the promise of making IMA more efficient. They argue that both types of platforms can potentially save time and money while achieving a high level of training. The authors describe similar benefits to those previously mentioned by more generic studies such as the availability, safety and time/cost constraints. Additionally, they emphasize the capability of VR systems in providing supplementary visual/auditory/haptic cues unavailable in the real world to enhance the task learning process. Furthermore, they also highlight the VR systems' power in simulating the task in a flexible way that adapts to users' needs and the training goals. While their study results with a significant difference in performance with the AR platform, in the form of less errors on tasks, they fail to obtain similar results for their VR setup. In order to justify this, they argue a likely ceiling effect due to the following two repetitions of the selected task for trainees that are expert technicians. In another preliminary study with the VR platform using the same task and the same procedure, but with twenty participants who lacked a technical background, the authors acquire similarly positive results to AR platform which suggests that VR training may indeed offer benefits over traditional training in some circumstances. They hold the assumption that, the VR and AR platforms will have considerable advantages over the traditional training especially under the consideration of complex tasks requiring high-level problem solving. The authors relate this advantage to these platforms' focus on enhancing the cognitive understanding of the tasks, helping with strategic planning. While drawing attention to lack of studies empirically evaluating the effectiveness of such platforms compared to traditional methods, the authors indicate their certainty that the costs of developing and updating these kinds of systems will become lower with technological advancements and the possibility that they will provide efficient training will increase. The authors conclude their research by arguing that novel training platforms can lead to less error-prone performance. Drawing from this argument, they conclude that the further development of VR and AR training systems are worth the investment for this exact purpose [Gav+13].

Following, we present two kinds of sensory feedback that have been commonly employed in the domain of VR training in addition to visual and auditory feedback. We give example application fields to give a better understanding on possible training scenario and refer to past work where possible.

2.3.1. Haptic Feedback in VR Training

Haptic feedback is one of the most prevalent supplementary feedback type that has been utilized to enhance VR training processes. It is often at its highest level of effect when associated with other sensory modalities [Mac00] and in commonly used as such in many virtual training scenarios. Through the simulation of the physical touch of virtual objects it can improve on the realism and immersion of virtual environments [FH21], and increase the sensory fidelity of VR [SG11][RNC18]. Following is a set of possible fields where haptic feedback is incorporated to further contribute to the virtual training process:

- **Medical training:** Inclusion of haptic feedback in this kind of training is shown to enhance training effectiveness and improve operation performance [CMJ11][Wan+17] Some specific applications of haptic feedback in VR training includes clinicial practices such as surgery planning and diagnostics [MS09] in addition to medical training such as laparoscopy [Iwa+11], arthroscopy [Bay+08] and palpation [Din+97].

- **Military training:** VR has been commonly used in this field to reduce personnel and material losses and improving the training effectiveness [Liu+18]. The supplementary adoption of haptic feedback can provide more realistic environments and lead to more efficient learning results to these virtual environments [Imm08]. Specific applications of this type of feedback in this field include safety and combat training [Lin+04].

- **Aerospace training:** VR training processes employing haptic feedback is commonly observed in this field [Bow94][Aba+09] to simulate plausible sense of touch through use hand-based haptic devices among others. The utilization of this sensory feedback within the field can lower operation cost by eliminating the need for limited resources [Sto01].

- **Sports training**: Integration of haptic feedback in this field is also common and remarked as beneficial [Zhu+20][FJ18]. Observed uses of this type of feedback in sports training includes aimed improvement on motor learning [LB07] and skill acquisition with additional sensory cues [Wu+21].

2.3.2. Olfactory Feedback in VR Training

Olfactory feedback has been adopted frequently in VR training instances due to its potential on enhancing the feeling of reality, diversification of user interaction modalities [GA11] and strength in stimulating memory recall [SSM92][GKR21]. Collection of specific use cases in training and education can be seen on the extensive review provided in Appendix B by Garcia-Ruiz et. al (2021). Following is a summary of fields where this type of sensory feedback can be utilized to contribute to the virtual training process:

- **Emergency response training:** VR training scenarios that simulate emergency situations can utilize olfactory feedback to replicate the smells associated with hazardous components such as fires [Cat94][Nar+19] or chemical spills without the risk of harm.

- **Medical training:** Olfactory feedback can be integrated into these type of training processes to simulate medical procedures or patient care. For example smell of disinfectants or certain chemicals can be replicated to help trainees better understand the sensory aspects of their work and make more accurate diagnoses [Spe06].

- **Military training:** Adoption of olfactory feedback in military training simulations can lead to more realistic and effective training experience. Virtual combat training can use scent diffusers to replicate smells associated with combat to create more believable experiences.

- **Rehabilitation training:** Olfactory feedback can be used in recovery and rehabilitation training to create more realistic environments and serve as stimuli treatment during therapy processes [Che06]. Given the olfactory channel's strong relation to memory recall, this type of feedback can be effectively exploited for relaxation training and treatment of PTSD [S H21].

2.4. Augmented Virtuality

In this section, we will make an introduction to the term AV. In order to do so, we will first review the reality-virtuality continuum and highlight AV's position on this continuum along with its main characteristics. The introduction of augmented virtuality will be followed by a review of existing studies on the topic and some previous fields of use. Furthermore, we will draw attention to possible advantages of the utilization of AV and recap our designation of it within our own research.

Reality/virtuality continuum is a continuous spectrum representing a real environment, a virtual environment and anything falling in between these two consisting of compositions of real and virtual objects. A real environment refers to an environment solely consisting of real objects within the physical world as opposed to virtual environment, which represents a completely virtual world without any real-life elements. The concept of reality/virtuality continuum was introduced by Milgram et al. (1994) and is illustrated in Figure 2.1. In their research, they view the real environment and the virtual environment as two concepts lying on the opposite sides of the continuum, instead of treating them as simply antitheses. Furthermore, they define a real environment as an environment that clearly must be constrained by the laws of physics, whereas the virtual environment is defined as and environment in which the participants are totally immersed in a completely synthetic world, which may mimic the properties of a real-world environment but which may also exceed the bounds of physical reality by creating a world in which the physical laws governing gravity, time and material properties no longer hold. Following these definitions, Mixed Reality (MR) environment is described as one in which real world and virtual world objects are presented together within a single display, anywhere between the extrema of the Reality-Virtuality (RV) continuum [Mil+94].

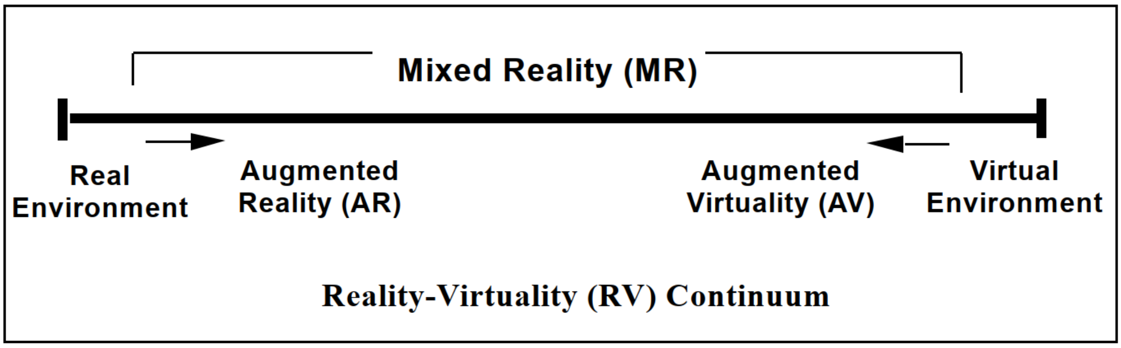


Figure 2.1.: Simplified representation of a RV Continuum [Mil+94]

The term AV defines a composite virtual environment augmented with real-world elements as opposed to Augmented Reality (AR), which represents an augmentation of a real environment with virtual elements. AV refers to a technology that enhances or augments a fully immersive virtual environment by adding real-world elements to it, such as haptic feedback, smells, or other sensory inputs. AV aims to increase the realism and immersion of the virtual experience by making it more similar to the real world. It can be experienced through VR headsets, or other types of immersive devices, and it can be used in various fields such as gaming, training and simulation, and therapy.

Within their research, Milgram and (1994) make a list of display concepts which are classified as Mixed Reality (MR) in order to distinguish the differences and similarities of these systems: [MK94]

1. Monitor based (non-immersive) video displays – i.e. "window-on-the-world" (WoW) displays – upon which computer generated images are electronically or digitally overlaid. Although the technology for accomplishing such combinations has been around for some time, most notably by means of chroma-keying, practical considerations compel us to be interested particularly in systems in which this is done stereoscopically.

2. Video displays as in Class 1, but using immersive head-mounted displays (HMD's), rather than WoW monitors.

3. HMD's equipped with a see-through capability, with which computer generated

graphics can be optically superimposed, using half-silvered mirrors, onto directly viewed real-world scenes.

4. Same as 3, but using video, rather than optical, viewing of the "outside" world. The difference between Classes 2 and 4 is that with 4 the displayed world should correspond orthoscopically with the immediate outside real world, thereby creating a "video see-through" system, analogous with the optical see-through of option 3.

5. Completely graphic display environments, either completely immersive, partially immersive or otherwise, to which video "reality" is added.

6. Completely graphic but partially immersive environments (e.g. large screen displays) in which real physical objects in the user's environment play a role in (or interfere with) the computer generated scene, such as in reaching in and "grabbing" something with one's own hand.

In previous studies, AV systems have been developed and employed with the intentions of realizing highly immersive environments. Some of these include a study by Gonzalez et al. (2020), where the authors use AV to increase realism and potentially increase presence to reduce stress. As part of their study, an experiment was conducted that sought to understand how sense of presence can be increased and how increased sense of presence can improve the intended outcome of an intervention delivered by immersive virtual reality technology. Their results suggest that augmenting the virtual world with items experienced concurrently in the real-world by the participant can increase sense of presence and that this augmentation enhanced the session, leading to greater reduction in the participants' stress levels, at the cognitive and physical levels [Gon+21]. In another study, Neges et al. (2018) present an AV system which integrates real operating elements in a virtual environment for head-mounted displays. By achieving high degrees of immersion with their approach, the authors are able to simulate various stress conditions while training maintenance tasks and form a basis for subsequent studies to examine the impact of the proposed stress scenarios during the execution of these task [NAA18].

In their demo and corresponding study, Nahon et al. (2015) enhance the VR headset experience with AV. As a result of the demo, they report multiple benefits from AV aspects of their system that are perceiving one's own body, the real world and other people. Some of the reported benefits include reinforcing the presence of virtuality and eliminating the odd feeling of not actually being there, providing a safer experience by preventing from dangers like hitting something, or falling, and reducing the claustrophobic effect of wearing an occluding headset [NSC15].

In two subsequent studies, Regenbrecht et al. (2003 & 2004) describe the concept, prototypical implementation, and usability evaluation of an AV based videoconferencing system. As a result of their evaluations focused on the general setup and on the usability of the system, they were able to prove their concept and show the potential for future productive use [Reg+03][Reg+04]. One study employing an AV system is from Albert et al. (2014), where the authors develop a high-fidelity AV environment that helps develop workers' hazard recognition skill through risk-free learning and immediate feedback, embed cognitive retrieval mnemonics to improve long-term retention of cues for construction hazards, and finally evaluate the effectiveness of the strategy as an intervention on active construction crew by using the multiple baseline testing approach [Alb+14]. Another more recent study including an AV system is conducted by Howard and Davis (2022), in which the authors perform a meta-analysis and systematic literature view to test their hypotheses on MR rehabilitation programs [HD22]. Both of the last mentioned studies conclude with results representing the effectiveness of AV in their relative fields.

On his master's thesis, Antoni (2021) develops a virtual process exploiting AV techniques in order to simulate a training session of special educators and help them acquire new skills in specific teaching techniques. Following his implementation, he performs an initial evaluation showing the potential of AV for teacher training purposes [Ant21]. On yet another recent study, Palma et al. (2021) present a system to improve engagement in a VR experience using inexpensive, physical, and sensorized copies of real artifacts made with cheap 3D fabrication technologies. By employing AV approaches, they overcome one of the main limitations of mainstream 3D fabrication technologies, which is a faithful appearance reproduction. As a result of their studies, they report that their system engages the user in the experience thanks to the touch interaction with the physical replica [PPC21]. Finally as part of their work, González et al. (2021) develop an advanced teleoperation and control system for industrial robots in order to assist the human operator to perform the mentioned tasks. Their proposed teleoperation uses AV and haptic feedback to provide the user an immersive virtual experience when remotely teleoperating the tool of the robot system. The authors conclude their study by showing the effectiveness of the proposed approach similarly to the previously mentioned studies [Gon+21].

2.5. Object Tracking

Object tracking is the task of identifying the location, trajectory and possible additional characteristics of a target object based on sensor measurement from devices such as cameras, radars, microphone, sonars or any others that can be utilized to obtain information about existing objects in the environment [Cha+11]. Typically, it refers to the tracking of an object within a sequence of images, based on the frames captured by a camera. In further detail, the analysis of the image sequence involves detection of the moving object and its classification, followed by a frame to frame tracking [BK17]. It represents a critical task in many computer vision applications including surveillance, robotics, augmented reality and driver assistance [CRM03].

Wide variety of systems across different fields leverage image based object tracking techniques to analyse object trajectories and understand their characteristics, in turn making intelligent decisions based on the acquired understanding of object behaviour. Despite its prevalence in the computer vision field and extensive research, it still remains a complex problem due to many factors. These factors include noise in images, partial and complete occlusion of objects, complex shape of objects, illumination changes of the environment and loss of information caused by projection of the 3D world on a 2D image [YJS06]. Given its relevancy in many fields and the complex nature of the problem, many methods have been researched and implemented to address object tracking. Some of these methods include contour based models, where the object are tracked by considering their outlines as boundary contours that get updated every frame, region based models, where the tracking of the object is based on the color distribution, and feature point based models, where feature points are extracted and utilized to describe an object [DT14]. We can broadly further categorize image-based tracking methods into two groups, learning based methods and non-learning based methods. As learning based methods tend to be more robust to complex conditions such as partial occlusions or illumination changes, they also have their own disadvantages over the non-learning based ones. In contrast to non-learning based methods, they require large amounts of training data and significant computational resources to train and run. Many different techniques exist when it comes to addressing the problem of object tracking and there is not a single perfect solution that applies to every scenario.

2.6. Digital Twin

A digital twin is a virtual representation of a physical object or system. They are used for simulation, analysis, and monitoring of the real-world counterpart in a wide variety of industries, and are one of the most promising enabling technologies for realizing smart manufacturing and Industry 4.0 [Tao+19]. Industries such as construction and transportation in addition to manufacturing adopt this technology and aim to optimize performance, predict maintenance needs, and improve decision-making with their incorporation. The digital twin is typically created using sensor data and other information collected from the physical object or system, and can be used to simulate how the physical object will behave under different conditions. By utilizing the data from the physical object, the digital twin evolves and keeps itself up-to-date, reflecting any change to the physical counterpart throughout the product lifecycle. Through the realization of this closed-loop of feedback between the virtual environment and the real world, digital twins enable companies to seamlessly optimize their products, production, and performance at minimal cost. [1]

[1] S. D. I. Software. *Digital Twin*. URL: `https://www.plm.automation.siemens.com/global/en/our-story/glossary/digital-twin/24465` (visited on 01/25/2023)

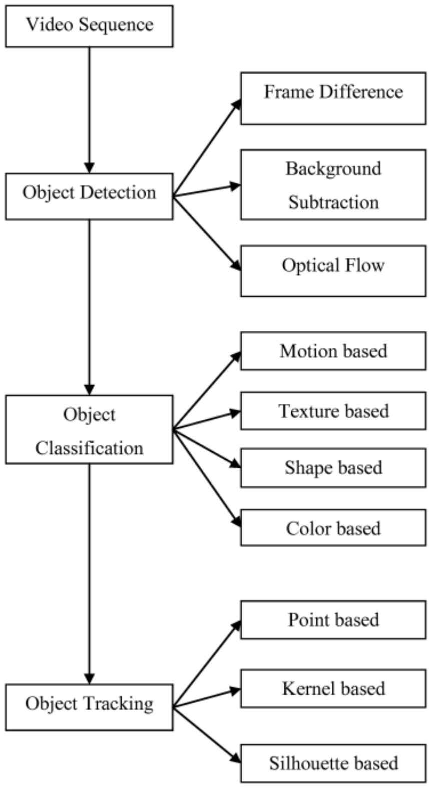


Figure 2.2.: Basic steps for tracking an object [BK17]

The types of industrial applications of digital twins have been identified as the applications in design phase, manufacturing phase, service phase and retire phase [Liu+20]. In Figure 2.3, concrete applications of digital twins can be seen listed in each of these types.

In other definitions, digital twins are classified in three types as follows: [1]

- Product Digital Twins: Adoption of digital twins with a focus on efficient design of novel products
- Production Digital Twins: Adoption of digital twins for the purpose of manufacturing and production planning
- Performance Digital Twins: Adoption of digital twins for the analysis and response of operational data

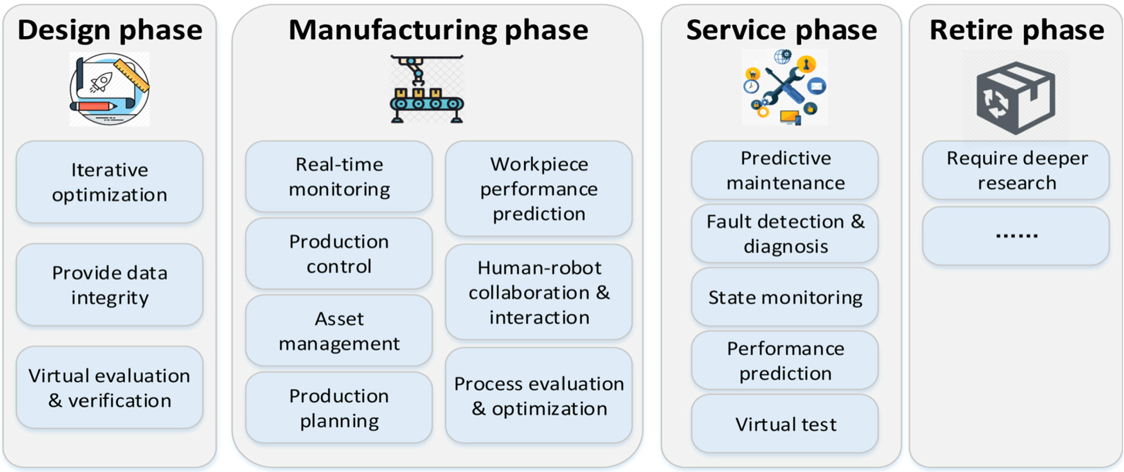


Figure 2.3.: Applications of digital twins distributed in different lifecycle phases [Liu+20]

3. Research Evolution

This chapter is divided into three sections, namely "Research Vision", "Initial Experiments" and "Design Changes and Adaptations". In the first section, we introduce the vision of our research, explain the initial ideas and goals, and how we plan on realizing them. The following section is dedicated to report on our initial experiments with certain tools and methods to potentially support the initial vision. Finally, within the last section we go through our adaptations of the initial ideas based on the experiences and findings from the previous section, and review the final design of our project with its levels.

3.1. Research Vision

In our research we focus on the effects of immersion and presence on learning within a virtual training process. In order to do so, our initial vision is to develop a system with varying levels of immersion. By designing and implementing multiple layers of immersion within our virtual training tool, we can not only evaluate its effectiveness in comparison to more traditional virtual training methods, such as watching videos or reading texts followed by quizzes, but also explore the potential effects of different levels of immersion on learning outcomes. The basis version of the developed system will be in the form of a VR training tool, allowing the users to interact with the virtual environment, which should already represent a considerable improvement on immersion compared to traditional virtual training processes that allow very limited interaction. The following versions of the system are to be built upon increasing levels of immersion, which are realized by introducing supplementary sensory feedback and employing augmented virtuality techniques. In addition to visual/auditory feedback, versions of our system is set to include haptic and olfactory feedback with the integration of devices designed to utilize such perceptive channels. Finally, we also envision the generation of an additional immersion level by building a version of our tool that includes augmented virtuality. Optionally, the system can also include a version that consists of a traditional virtual training process with minimal immersion, e.g. only a video with no virtual environment, serving as the most basic level for comparison.

For the design and development of a virtual training process, we select a scenario revolving around the interactions and training with the tool Machinery Fault Simulator - Rotor Dynamics Simulator (MFS-RDS). Machinery Fault Simulator is a tool specifically designed to create a safe and controlled environment for replicating common machinery faults and to study their signatures. While interacting with the device, it becomes possible to observe different vibration signatures, acquire a better understanding of what they represent and get trained on potential measures to take when such signatures are experienced. By simulating the properties of real world machinery in a controlled environment, MFS-RDS represents a learning platform that helps gain an understanding of the machinery dynamics without putting the real production at risk. The whole setup fits on a desktop and is capable of introducing various faults depending on the user requirements. The device itself is quite effective for introducing the concepts of predictive maintenance and training personnel within this area. [1]

Figure 3.1.: MFS-RDS with multiple discs attached along the shaft [2]

Some potential training scenarios and tasks we can utilize for the virtual training process are as follows:

- Using the MFS-RDS for mechanical applications such as alignment and balancing
- Installing, removing, replacing and servicing of components such as rings, bearings and coupling
- Interpreting the shaft centerline orbit plots

[1] I. Spectra Quest. *User Operation Manual for Machinery Fault Simulator – Rotor Dynamics Simulator (MFS-RDS)*. Spectra Quest, Inc. 8227 Hermitage Road, Richmond, VA 23228

[2] I. Spectra Quest. *Machinery Fault & Rotor Dynamics Simulator*. URL: https://spectraquest.com/machinery-fault-simulator/details/mfs-rds/ (visited on 06/06/2023)

- Detecting and fixing the misalignment of couplings, bearings and pulleys
- Unpacking and assembling the MFS-RDS
- Oil pump system operation

In order to realize increased immersion within the virtual training process, our initial research has focused on multi-modal interaction with the virtual environment and additional feedback channels, namely haptic and olfactory. Both of these feedback types can significantly increase immersion within a virtual environment by providing users with a more realistic and engaging sensory experience. By incorporating the additional corresponding feedback mechanisms into our virtual environment, it would be possible to make users feel more present during the training process. As an example, haptic feedback can be incorporated to simulate the sensation of physical objects while interacting with their virtual counterparts. In our specific use case, one good example would be simulating the touch of a screw or bolt as the user is interacting with such object within the virtual environment. For the olfactory feedback, one can possibly simulate the smells of our virtual environment, e.g. oil smell. By employing these feedback mechanisms, we can enhance the virtual training process by helping the users feel more connected to the virtual world and create more immersive experiences that engages multiple senses where users feel more present within the virtual environment.

With the intention of realizing yet another level of immersion for the virtual training process, our initial vision also takes into account the employment of augmented virtuality approaches. As suggested from the reviewed work within Section 2.4, we expect positive outcomes from utilizing augmented virtuality techniques as part of our virtual training tool, especially when it comes to increase immersion. Considering these results, we anticipate our own AV approach to have a positive impact on immersion, and consequently lead into an improved learning outcome within a virtual training process.

In order to introduce additional levels of immersion within the augmented virtuality variant of our proposed system, the initial plans consist of including following versions of the system:

- **AV Sublevel 1**: Augmentation of the virtual environment by visualizing real-world MFS-RDS inside it (e.g., by utilizing a passthrough window)
- **AV Sublevel 2**: Augmentation of the virtual environment by letting the user directly interact with the real-world MFS-RDS while visualizing a virtual counterpart by tracking parts of the machinery.
- **AV Sublevel 3**: Augmentation of the virtual environment by letting the user directly interact with the real-world MFS-RDS while visualizing a larger scale virtual counterpart, representing real-world industrial machinery that the MFS-RDS is intended to simulate.

For the sake of realizing AV Sublevel 2 and AV Sublevel 3, the virtual training tool has to have some sort of tracking enabled. By employing techniques to track the MFS-RDS and its individual parts, it would be possible to replicate the direct interactions with the real-world device on its virtual environment counterpart. To be able to track MFS-RDS, either physical or image-based tracking techniques have to be adopted. However, even though physical tracking can be quite robust and accurate, it is not suitable for our scenario. This is due to the fact that we aim to track individual parts of the RDS motor, which can be quite small and impossible to equip with physical trackers. For tracking within our setting, we focus on image-based tracking techniques. Furthermore, we prioritize the non-learning based tracking methods over the learning based ones for our research, due to their flexibility on working with custom objects. By doing so, we aim to avoid the requirement of a training set generation for our MFS-RDS objects to track. The adoption of such techniques requires no prior learning and therefore leads to faster integration of new objects.

Another method to realize tracking of MFS-RDS is utilizing a marker-based tracking approach instead of tracking the objects directly. Fiducial markers such as ArUco can potentially be used to track the objects within the real environment by getting attached to fixed positions on these objects. However, it should be noted that with this approach the tracking of smaller individual machine parts such as screws would be impossible due to their small size. One other possible approach is the indirect tracking of the real-world objects through hand tracking. In the case where the hand tracking is successfully realized, the currently interacted real-world object can be assumed to have a fixed position relative to the tracked hand. It is still important to mention that this approach has some limitations and needs some adjustments. The first limitation is that while the object of interest can be indirectly tracked once being held by the hand, it offers no way of inferring the orientation of it, but only the estimate position. Furthermore, we should still include some sort of trigger to determine when the object starts being held by the hand. One option for that can be having the to-be-tracked objects in a fixed place within the environment and snapping the virtual representations of the object to the virtual hand once a certain grip gesture is detected, such as a pinch. Even though these last proposed tracking approaches have their limitations, they still represent fallback methods to standard image-based techniques for the integration of MFS-RDS tracking on the AV variants of our proposed system.

During the design phase of our proposed system, another requirement we have set for ourselves is the plausible representation of a virtual environment. It is important to have a realistic looking environment serving as an immersive platform for the interactions with the device. We envision to create such environment by replicating a real work laboratory surrounding the MFS-RDS we have on site. We aim to have a set of models within our virtual environment that serve as accurate representations of the objects in lab. Furthermore, we need to ensure that these models are equipped with realistic materials and the whole environment is lit with adequate lighting. We do not only limit ourselves to realistic visuals but also intend to make use of auditory perception to further immerse the users within the virtual environment by using accurate sound effects and audio cues. Moreover, we plan on ensuring realistic physical properties within the virtual environment, while still keeping usability in mind. By adhering to these requirements, we anticipate an increase sense of immersion and presence during the interaction with our proposed virtual training process.

Our work on this research does not focus on the implementation and/or design of feedback components from scratch. Instead, existing devices in the market are to be employed and these tools need to be logically integrated into our proposed system. It should also be noted that an accurate evaluation of the proposed virtual training process regarding the impact on learning requires a substantial amount of user data to be collected through user studies. Since our proposed system utilizes specific hardware for the training scenarios, some data has to be explicitly collected on-site which severely limits the rate of trainee data collection. In order to overcome this issue, we need to ensure that all the components of the training setup is sufficiently mobile where we can (i.e., the versions without the real-world MFS-RDS employed for augmented virtuality) so that data collection is not limited to a single location. Furthermore, we should also pay attention to the comfort of use for our system during our development. It is essential to make sure that the system never feels too cumbersome or hard to use, so that the sense of immersion is not broken.

3.2. Initial Experiments

In order to validate our initial vision and design ideas, multiple tools and methods have gone through trials as part of our research. By collecting experience with these potential techniques and devices, we end up with better assessments on their value and plausibility regarding their integration into the proposed system. In this section, we introduce these tools and methods we have based our initial experiments on and review our experiences.

Unity game engine is chosen to serve as the base development platform for our virtual training process. This is not only due to its capabilities when it comes to developing Extended Reality (XR) applications, but also because of own aggregated experience with the tool. Since our research focuses on multiple new tools and methods, it is not feasible to get acquainted with a newly introduced tool within the scope of our research. We designate Oculus Quest 2 as our target VR headset, given its technical capabilities, ability to track controllers without any external base stations and to run our proposed tool standalone without any cables. Furthermore, the hand tracking feature of Oculus Quest 2 can be another improvement on the immersion of our virtual training process and serve as another utility if we opt for indirect tracking of the objects in the AV version.

As we set Unity as our base development tool, we also consider the potential integration with the game engine as we assess the hardware and software we experiment with.

With the intention of realizing an olfactory based immersive setup, we focused part of our initial experiments on OVR ION, a supplementary device that can be attached to a VR headset to emit scents. The wearable scent device is capable of emitting scents that correspond with specific events or scenes in a virtual environment and providing an additional sensory input that can contribute to a more engaging and realistic VR experience. The device utilizes scent cartridges that can be swapped out, and it can be controlled through a mobile app that communicates with the device over Bluetooth Low Energy (BLE). Additionally, the device features a Unity plugin that facilitates integration with VR experiences implemented using the game engine. It has a sufficient battery life and a low weight making it quite portable and suitable for integration.

Figure 3.2.: OVR ION [3]

In order to incorporate haptic feedback into our virtual training process, we focused our initial research on the experimentation with two haptic devices, namely SenseGlove and Hapticlabs DevKit. The SenseGlove is a haptic device designed to provide realistic tactile feedback in virtual reality and other digital environments. The device fits over the user's hand and uses a combination of sensors and actuators to simulate the sensation of touching virtual objects. The SenseGlove can be integrated with VR experiences implemented both with Unity and Unreal Engine by its dedicated plugins and it can be programmed to provide different types of haptic feedback based on the application. Not only is the set of gloves capable of generating force feedback to simulate mechanical stimuli, they are also equipped with vibration motors to make use of additional tactile feedback. The gloves are designed to be comfortable and easy to use, with a lightweight and ergonomic design that allows for extended use without causing fatigue. However, it should still be noted that extended use of the device can lead to discomfort due to potential heating issues. SenseGlove and its accompanying Software Development Kit (SDK) makes it possible to simulate the touch of objects of different shapes, sizes or kinds such as rigid, squishy and breakable objects. Having these capabilities considered, SenseGlove represents a tool of high potential regarding the possible increase of immersion and presence for our virtual training tool.

[3] O. Technology. *The Science - OVR Technology*. URL: `https://ovrtechnology.com/` (visited on 04/30/2023)

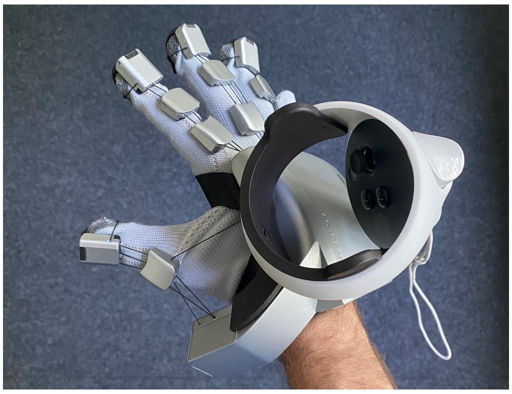


Figure 3.3.: SenseGlove with an Oculus Quest 2 controller attached for wrist tracking

The Hapticlabs DevKit on the other hand is a software and hardware development kit designed to facilitate the creation of immersive haptic experiences for digital applications. The development kit consist of a range of hardware components, including actuators and controllers, as well as a SDK that provides a variety of tools and resources for developers. The Hapticlabs DevKit is designed to be modular and customizable, allowing developers to build tangible interactions tailored to their specific needs and use cases. The development kit includes a library of pre-built haptic effects, as well as a programming interface for creating custom haptic effects. Unlike SenseGlove, the haptic feedback with this tool kit is not generated from a wearable glove, but instead a set of varying output devices such as Eccentric Rotating Mass (ERM), Voice Coil (VC) and Linear Resonant Actuator (LRA). These actuators can potentially be strapped on different body parts and connected to the so-called satellite, waiting to be triggered by other connected input devices, e.g. buttons or touch panels. Even though Hapticlabs does not offer a Unity plugin at the time of research, it is still possible to integrate the hardware into a project developed with the game engine by using serialization and not depend on external input triggers to generate haptic feedback. Once connected to the same device running the project, the haptic tracks previously saved on the satellite can be triggered by function calls including the track name as the parameter. In addition to using previously designed signal tracks on Hapticlabs Studio, it is also possible to generate varying pulse and vibration signals at runtime by utilizing the exposed signal parameters such as duration, intensity and frequency. By doing so, the dependency on external physical triggers is removed and it instead becomes possible to trigger the actuators directly through C# scripts in Unity, leading to an increased adaptability. Furthermore, the satellite unit makes use of two channels which are capable of triggering varying signals on two different types of actuators. With the possibility of using multiple channels and generating a virtually infinite set of different haptic signals, the tool is capable of simulating haptic feedback that can be adjusted to one's needs in order to create more immersive experiences.

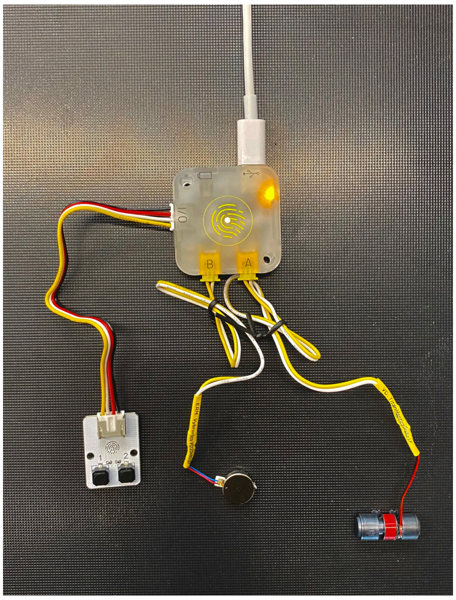


Figure 3.4.: Hapticlabs satellite connected with an input unit along with an ERM and VC on separate channels

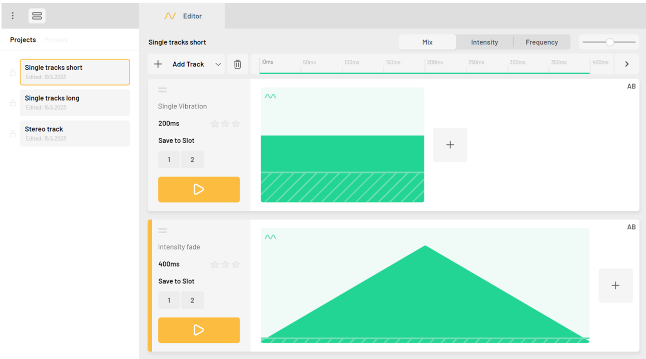
For the AV variants of our proposed system, it is required to adopt an image-based tracking technique. Therefore, part of our research phase has been initially reserved for following non-learning based tracking methods among others which have been left relatively out of focus:

- **Region-Based Gaussian Tracker (RBGT)** [4]
- **Sparse Region-Based 3D Object Tracking (SRT3D)** [5]

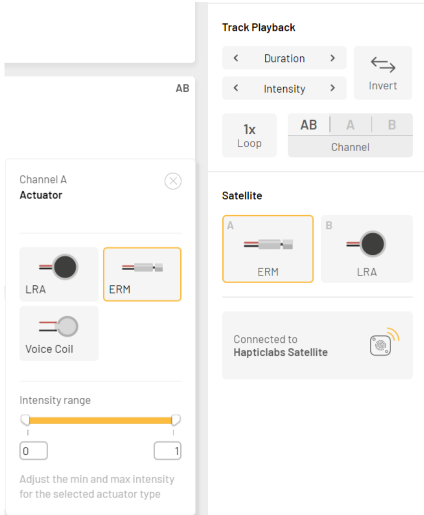
Both of the above tracker implementations have their complete source code published, with the latter being a more recent and advanced approach compared to the former. Either of the two published projects have an evaluation on the Region-based Object Tracking (RBOT) data set included and employ Azure Kinect camera for their implementations. However, it is possible to use different cameras for both implementations and our research reveals that other external work achieved satisfactory results with their integration of RBGT using a mobile phone camera, even though exact specifications are unknown.

[4] M. Stoiber, M. Pfanne, K. H. Strobl, et al. *Region-Based Gaussian Tracker (RBGT)*. URL: `https://github.com/DLR-RM/3DObjectTracking/tree/master/RBGT` (visited on 02/28/2023)

[5] M. Stoiber, M. Pfanne, K. H. Strobl, et al. *SRT3D: Sparse Region-Based 3D Object Tracking*. URL: `https://github.com/DLR-RM/3DObjectTracking/tree/master/SRT3D` (visited on 02/28/2023)



(a) Example set of tracks with varying frequency and intensities



(b) Choice of actuator units for separate satellite channels

Figure 3.5.: Screenshots from Hapticlabs Studio depicting the preparation of tracks and satellite setup

Since we designated our VR target headset as Oculus Quest 2, our instinctive idea was to employ its own cameras for the tracking itself. Refraining from the use of an external camera for tracking would make the development process much smoother, helping us avoid transformation from one camera space to another for syncing objects in the virtual environment. However, our initial research revealed that it is not possible for apps using Oculus Passthrough API to access the videos of the physical environment captured with the Oculus Quest 2 cameras. As the raw images from the device sensors are exclusively processed on-device and are not exposed to the developer through the Application Programming Interface (API) in any way, it is not possible to access the image sequence captured by the devices own cameras. [6] Given these conditions, we employ an external camera for the task of tracking, namely Logitech BRIO. It is a high-end webcam supporting multiple resolutions and has the following relevant technical specifications: [7]

[6] O. VR. *Mixed Reality with Passthrough*. URL: `https://developer.oculus.com/blog/mixed-reality-with-passthrough/` (visited on 02/04/2023)
[7] Logitect. *BRIO Ultra HD Pro Business Webcam*. URL: `https://www.logitech.com/en-us/products/webcams/brio-4k-hdr-webcam.960-001105.html#specs` (visited on 02/14/2023)

Supported Resolutions:

- 4K/30fps (up to 4096 x 2160 pixels)
- 1080p/30 or 60 fps (up to 1920 x 1080 pixels)
- 720p/30, 60, or 90 fps (up to 1280 x 720 pixels)

Diagonal Field of View (dFoV): 90°/78°/65°

In order to acquire the calibration data such as the calibration matrix, average projection error and distortion coefficients for our external camera, we utilize an online database. [8] Since the camera is capable of operating in multiple resolutions and the database does not include entries for all three resolution settings at the time of research, we make use of the calibration procedure offered on the same platform where one needs to align the camera view with patterns shown on the screen by using a print of a grid or a secondary screen. After this process, we possess an accurate set of calibration data for our external camera, ready to be used for our implementations and tests.

After initially failing to set up the SRT3D project on our devices, we shifted our focus to setting up RBGT since this is a predecessor of the more advanced implementation and both projects share similar structures. Both implementations are shared in the form of CMake projects and have a set of external dependencies, namely Eigen3, OpenGL, OpenCV, GLEW, GLFW3 and optionally Azure Kinect SDK. Following extended trials and failures of configuring the RBGT CMake project, vcpkg [9] has been employed to successfully install the aforementioned libraries and address the dependencies. Following the successful configuration and build of the RBGT CMake project, the experiments have continued with try-outs of tracking on recorded sequences and evaluations on the RBOT data set. Even though we were able to get the project in a state where it would compile and visualize set of frame sequences given as the input, additional runtime errors have been faced when the tracking was triggered. It's been detected that the runtime tracking error of the implementation was due to failed initialization of the models and to be more specific, the failed attempt at generating valid contours as part of the model point data generation. One potential reason of this could be the failed loading of additional Dynamic-link library (DLL)s that should come with the opencv[tbb] packages which has also been installed during our setup. However, it is likely that the root cause of the error is another issue, given that there are built-in parallel backends that the system can fall back to in case oneTBB library failed to load. At this point in our research, we made the decision to terminate our trials with the RBGT and SRT3D implementations since they were consuming too much of our resources and concluded that the AV version of the proposed virtual training tool needs to integrate tracking with alternative ways.

[8] `https://www.calibdb.net/`
[9] `https://github.com/microsoft/vcpkg`

After the initial experiments and following assessments of the supplementary feedback devices and the failed integration of tracking libraries, adaptations have been made to our initial vision in order to adjust for the updated conditions and the time constraints. In the following section, we go through the design changes we made based on our initial experiments and review the finalized concepts before we continue with the actual implementation of the proposed virtual training process.

3.3. Design Changes and Adaptations

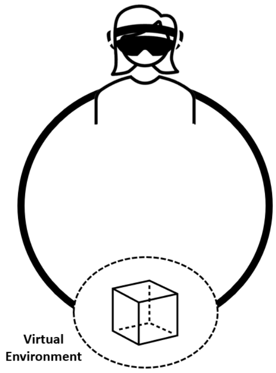
In response to the insights gained from the initial experiments and the challenges encountered, a series of design changes and adaptations were made to refine and align our proposed system with the evolving requirements. This section delves into the adjustments made on our initial vision based on the outcomes of these experiments. Through careful evaluation and consideration, these adaptation were found necessary to ensure the feasibility, effectiveness, and timely completion of our proposed virtual training tool. The subsequent discussion presents a review of the revised concepts, highlighting the rationale behind each decision and their implications on the overall project trajectory. Throughout these design changes, we respected our initial requirements such as generating an immersive virtual training process which allows us to make evaluations and discussions on the learning outcome. Furthermore, with our updated concepts we still maintained our initial idea of implementing a virtual training tool with varying immersion layers, which can potentially help us acquire a better understanding of the effect of immersion and presence on the learning outcome. We start the review of design updates and adaptations with supplementary feedback components, continue with changes on the augmented virtuality version of the tool and discuss the newly adopted approaches regarding the tracking. In addition, we present the overall virtual training tool with the finalized immersion level divisions along with their integration with the actual training case.

Despite the potential benefits of olfactory feedback and the initial perceived suitability of OVR ION, this mechanism has been thrown out of focus during the design of our immersion levels and training cases. This was mainly induced by the fact that our training cases were not suitable for such feedback, as the real environment where the MFS-RDS is operated did not have many distinct smells. Some of the very few potential scents that we considered were the oil smell of a machine and a burn smell, which can potentially be emitted during a faulty operation of the machine. Due to the scarcity of frequent distinct smells in the real environment and the limited range of scents available through the olfactory device we had access to, we decided to set aside this feedback mechanism and instead prioritize haptic feedback for enhanced immersion and presence.

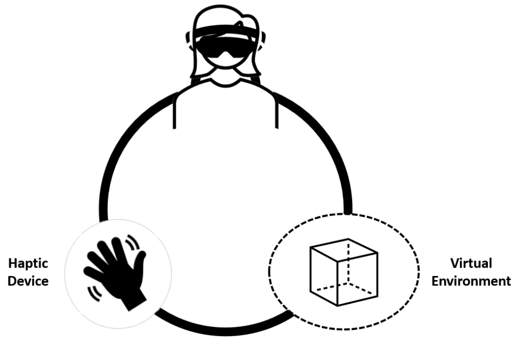
Although we had initial plans of having immersion sublevels within the augmented virtuality version (Level 3) as previously introduced in Section 3.1, we opted out of the realization of these sublevels for the development of our tool. Among others, these sublevels included a version where the real-world MFS-RDS is tracked and overlayed with a different, larger-scaled virtual machinery that represents a bigger real-world variant of the interactable device. The choice of abandoning these sublevels was caused by the vast physical proportions of the actual motors that the MFS-RDS mimics. In addition to not being able to translate directly from the training case to the actual real-world motor interactions, the projection of the small scale MFS-RDS to significantly large size machinery can introduce new usability problems. While some of the interactable parts of the simulator are limited to palm-size and can be easily interacted with using hands, the large motor counterparts can be up to hundred times larger in size and therefore cannot even be interacted without the use of other additional machinery in real world. Furthermore, the projection of interaction with MFS-RDS on the large-scale machinery could lead to small positioning errors getting magnified to the range of meters, which would not be plausible for the real-world scenario. By taking these into consideration, we made the decision of abandoning these sublevels and limiting the virtual training process to only three overall levels of immersion.

With the intention of obtaining increased immersion by integration of haptics as supplementary feedback mechanism and augmented virtuality methods, we envision to realize a virtual training process consisting of varying immersion levels as represented on Figure 3.6. While Level 1 consists of a standard VR experience, the subsequent levels are versions of the tool building on top of the base level with the same setting but with varying interactions due to newly introduced devices and techniques. Level 2, namely Haptics VR, is an extension of the initial level of immersion which incorporates additional input/output devices to generate haptic feedback for the user during interactions with the virtual environment. On the other hand, Level 3 represents an augmented virtuality setup where the virtual environment is augmented with real-world elements, i.e., the physical touch of real-world objects. This is planned to be achieved by tracking the real-world objects with an external camera that can potentially be attached on the VR headset and overlaying the real-world components with their virtual environment counterparts.

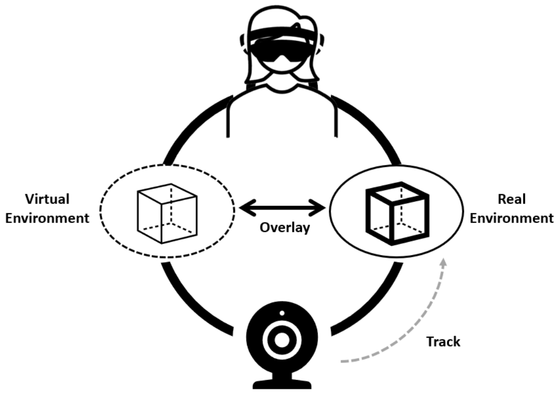
For our actual training scenarios, we mainly focus on using the MFS-RDS for mechanical application of balancing with the goal of providing training process users with a comprehension of the unbalance problem and creating basic intuitions of the physics behind it. By doing so, we aim to develop an immersive virtual training platform that is not only able to train the users specifically on the simulator tasks, but also equip them with insights which they can apply for balancing of large-scale machinery the interaction device simulates. With the use of such an immersive virtual training tool, the users can be trained on predictive maintenance while staying engaged.



(a) Level 1 – Basic VR



(b) Level 2 – Haptics VR



(c) Level 3 – Augmented Virtuality

Figure 3.6.: Levels of Immersion

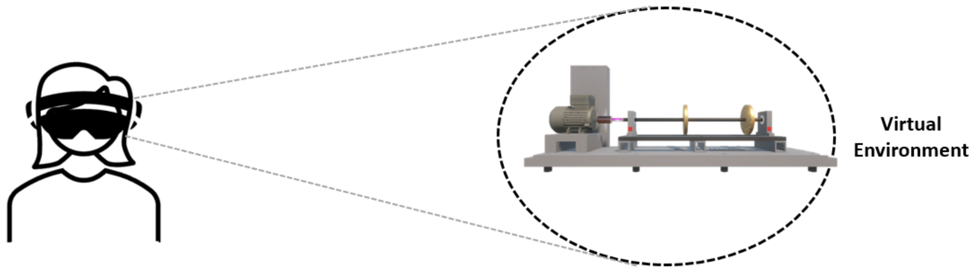


Figure 3.7.: Level 1 – Basic VR Training Case

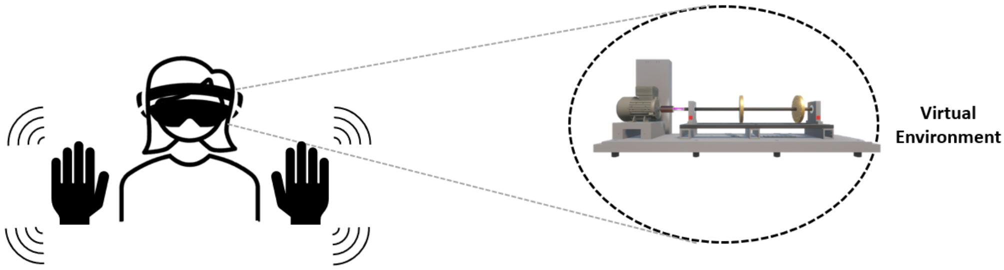


Figure 3.8.: Level 2 – Haptics VR Training Case

For the Level 2 of our proposed tool, we designate SenseGlove as our haptic feedback device and focus on its integration on top of the base level. Our initial experiments show that this device can be quite beneficial regarding improvements on the feelings of immersion and presence. With its capability of simulating touch of grabbable MFS-RDS components such as the discs and fixed objects such as the machinery foundations, a senseful integration of the haptic device into the second level of our tool will lead into a further immersive variant and foreseeably higher user engagement.

Finally, for the final level of immersion, we decide to employ different set of methods considering our experiences from the previous experiments with tracking. In order to have an initial working version of this level of immersion, we shift to the use of ArUco markers. By utilizing these fiducial markers, we can still track individual parts of the MFS-RDS without depending on more complex image-based tracking techniques. Especially fixed parts of the machine can be conveniently detected in real world and their virtual counterparts can be spawned within the virtual environment in correct location. Even though other interactable moving parts of MFS-RDS such as the discs can also still be tracked by employing markers, when it comes to smaller objects such as screws, this

[10] MFS-RDS image received from I. Spectra Quest. *User Operation Manual for Machinery Fault Simulator – Rotor Dynamics Simulator (MFS-RDS)*. Spectra Quest, Inc. 8227 Hermitage Road, Richmond, VA 23228

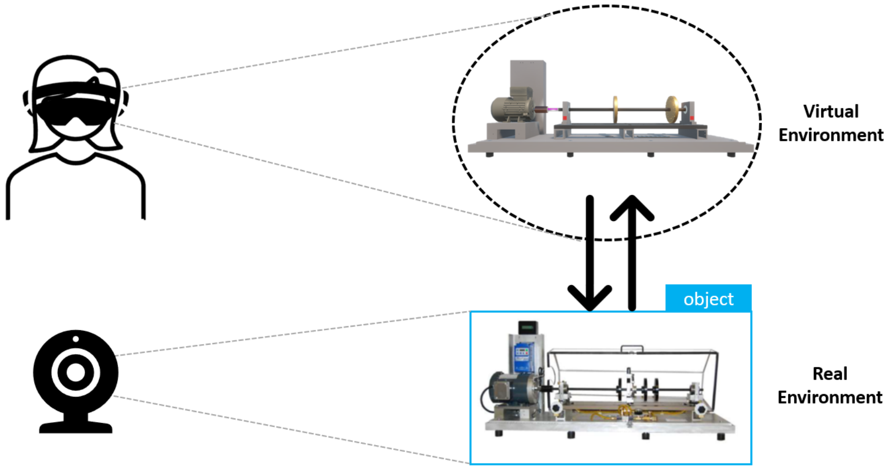


Figure 3.9.: Level 3 – Augmented Virtuality Training Case [10]

tracking approach represents limitations. In order to address these limitations and to be able to track small grabbable objects, we resort to an indirect tracking of objects through hand tracking. With the integration of hand tracking within our virtual training tool, which is possible through Oculus SDK, we can accurately determine the location and orientation of hands. For recognizing the first interaction with the screws and when they are actually being held by hands, we initially place them in fixed positions in real world and detect a pinch gesture within their proximity. This is followed by the snapping of the virtual counterpart to a fixed pose within the hands and indirect tracking of the real-world object. In the following iterations, we aim to further improve the tracking of these objects by an approach based on color masking. The screws are to be painted in distinct colors that are not present elsewhere in the real environment, so that they can be located by our external camera and placed within the virtual environment to a certain degree of accuracy. By extending the initial implementation with color masking technique, we can potentially eliminate the requirement of placing the objects in fixed locations within the real environment.

Throughout the following section, we review the implementation of these design ideas for our virtual training process. We go through the core components building our tool and also individual immersion levels in detail.

4. Implementation

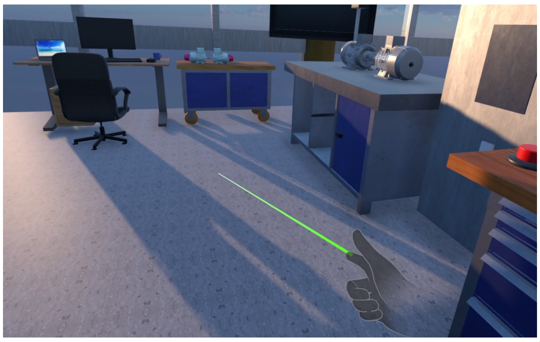
As we review the implementation of our virtual training tool, we go through each level of immersion separately. Since the first level of immersion builds a foundation for the latter two and these levels are extensions of the first one, we present the common core components as part of the first level. These components to be reviewed include the environment of the virtual training tool, along with common interactables such as parts of the MFS-RDS itself. We highlight any differences or extensions to the first level on the sections dedicated to the specific version of our tool.

4.1. Base VR Level

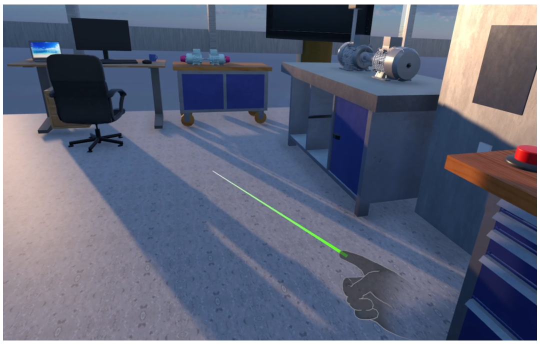
First immersion level of our virtual training tool serves as the base level for the other extensions. It represents a VR application with the setting of an environment replicating a work laboratory. In order acquire good graphics while still maintaining satisfactory performance, we set Unity's Universal Render Pipeline (URP) as our render pipeline. Besides a detailed model of MFS-RDS and its workstation, the environment is equipped with additional props to create a more detailed and realistic representation of the laboratory. By incorporating realistic visuals and high frame count, we aim to ensure high immersion during the virtual training process without any breaks.

We employ Oculus SDK to realize the VR Camera Rig and basic VR interactions. Even though the training scenario only consists of interacting with the MFS-RDS located on a fixed workstation, we extend the locomotion with teleportation so that the user is not limited to a stationary setup but has freedom to explore the whole environment. It should be noted that this mechanic does not work by default on the version of our tool which employ hand tracking and needs to be readjusted.

Despite finalizing this version without hand tracking and instead opting for a controller based interaction, we still experimented with different interaction types to assess which one suits the current immersion level the best. These interaction types consist of basic controller based interaction, controller based interaction with synthetic hands and hand tracking based interaction. Besides the actual interaction with objects within the scene, one noteworthy difference of the hand tracking version with regards to others is the teleport mechanic. In order to replace the thumbstick based teleportation controller based versions, we implemented a method based on hand gesture recognition. As seen on Figure 4.1, we utilize the finger gun gesture to initialize and confirm a teleport



(a) Finger gun gesture pending confirmation

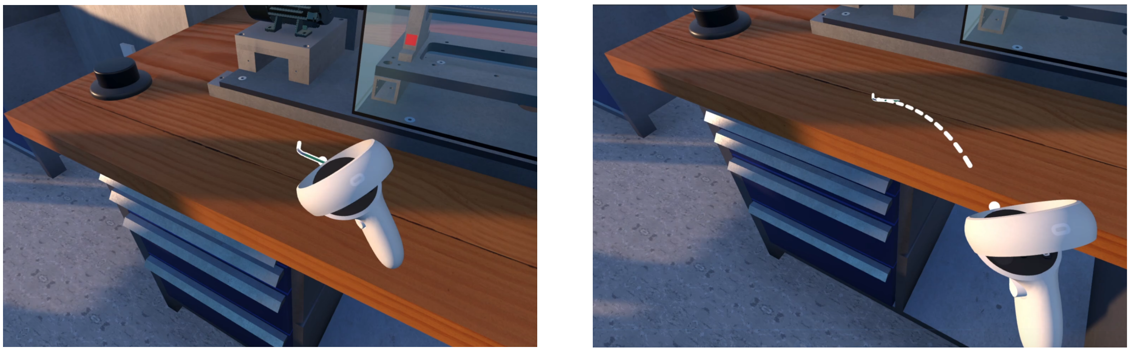


(b) Teleport trigger through gesture change

Figure 4.1.: Teleportation with hand tracking

command while using a ray sourced from the hand to determine the target location. In an effort to further improve this technique of teleportation, we replace the initial ray source of index finger tip with the wrist instead. By doing so, we obtain a more accurate teleport execution compared to the initial version that is error-prone due to movement of the index finger as the the teleport is confirmed. Nonetheless, it should be noted that this method represent some limitations. One limitation is that the gesture to execute the command may not be intuitive for all users. Another limitation is that the teleport target cannot be precisely selected at all times, especially in the case of non-steady hands. With the exception of teleportation command, all of the hand tracking based interactions are more intuitive compared to controller based interactions. Through eliminating the requirement of learning controller input mappings and being more intuitive in general, hand tracking based interaction introduces an increased immersion to the virtual training tool. Regardless, we decided to reserve hand tracking only for the final immersion level and utilize controller based interactions for the base level.

As previously indicated, the controller based interaction splits into two types, namely the basic interaction and synthetic hand interaction. While both of them employ a physical controller for input, the latter replaces the virtual controller models with hand models, visualizing the intended actions such as pinching and gripping of objects through accurate display of hand gestures. Even though the synthetic hand variant is more physically accurate and therefore more realistic, the basic version still offers its own advantages. Since physical accuracy is already out of scope on the basic controller based version, interactions with the objects can actually be designed in an easier, smoother way. This is due to the fact that unlike the synthetic hands, this version is not constrained by the physical properties of the interactable object. While we have to account for operable contact points of objects with the synthetic hands especially during the pinch interaction, this requirement is eliminated on the basic version. Instead of equipping interactable objects with convex hull part colliders, we can simply detect a collision between the controller model and a bounding box around the object, followed by its snapping to the



(a) Display of touch grab (b) Display of distance grab

Figure 4.2.: Basic controller based grab interactions

closest point on the controller model. Furthermore, the basic controller based interaction offers a distance grab mechanic in addition to touch grab, making the interactions with smaller objects particularly easier.

Although basic version excels in usability compared to synthetic hand variant, we still designate the latter as our interaction type due to its improved realism. The synthetic hand variant offers accurate visualization of hand gestures and natural manipulation of interactable objects, in turn creating a more realistic and immersive training experience. Despite its drawback in usability, we aim to enhance the user engagement with the heightened realism and foster a stronger sense of presence in the virtual environment, ultimately leading to more effective training outcomes.

In addition to the supplementary interactables such as drawers, the main interactable objects within the environment consist of the MFS-RDS parts, screws and an allen key used to interact with some of the machinery parts. The discs of the MFS-RDS serve as the objects of highest relevancy for the training scenario. Through the interaction with these discs, users are able to fix an unbalance of the shaft that is introduced by the simulator and acquire a perfect balance of the machinery. This is done by attaching screws on the fixed weight slots that are located on the disc. In order to transmit an occurrence of unbalance to the trainee, we emphasize the deviation of shaft center-line during its rotation. By exaggerating the visual outcome of the unbalance on the MFS-RDS we make the effects of this problem more perceivable and understandable. With an improved balance of the simulator led by correction steps done by the trainee, the deviation from the shaft center axis is lowered and eliminated completely in case of a restored perfect balance. With these set of interactions, our goal is to give the users a training platform where they can familiarize themselves with the unbalance problem and develop an understanding of its underlying physics. Furthermore, by activating a warning alarm when a potential hazard condition is detected, we aim to train users on safety measures and precautions while operating the machine.

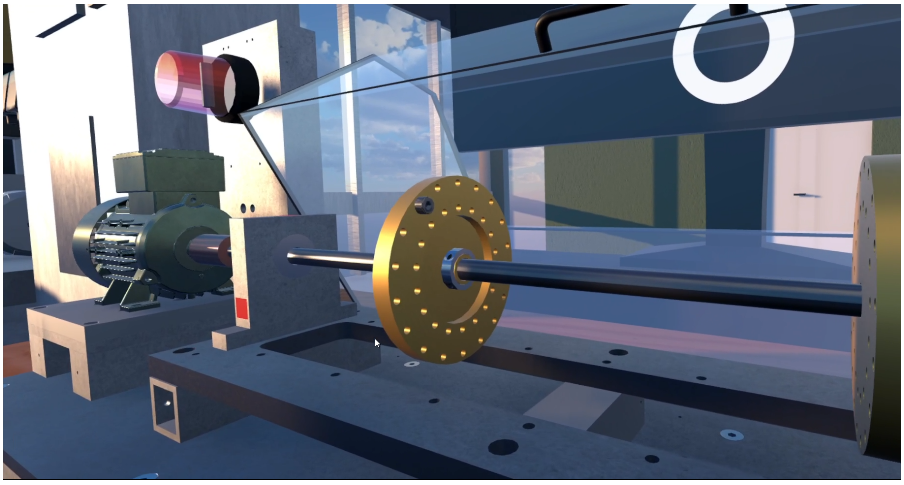


Figure 4.3.: MFS-RDS discs with a single screw attached for balancing

In order to guide the users through the steps to resolve an unbalance, we display a set of instructions on a television screen within the environment. We use the same screen to display visual representations of the shaft centerline orbit when an unbalance is present, and we make adjustments accordingly when there are any changes in performance, whether they are improvements or deteriorations. In addition to on-screen instructions, we also display holograms to highlight screw slots on the discs and target disc positions along the shaft. Utilizing these holograms, we draw attention to key regions for the unbalance fix such as the optimal screw slot and effective disc positions. Moreover, we employ additional visual cues including the highlighting of interactable drawers, grabbable objects and the training area under right conditions to enhance the guidance of the user throughout the whole training process.

With the intention of improving on the realism aspect of the virtual environment, we equip our scene objects with visually accurate Physically Based Rendering (PBR) materials. In order to do so, we first ensure that all our models have valid geometries and are UV mapped. These geometrical adjustments and the UV mappings are done using Blender and followed by the reimport of the updated models into our project. Once our models are ready and reimported, we seamlessly integrate the PBR materials inside the Unity project, providing lifelike textures, reflections, and lighting properties. On top of the visual improvements, we incorporate a set of various sounds into our training environment. By integrating these sounds along with the improved visuals, we aim to create a realistic and immersive ambiance, elevating the overall sense of immersion and presence within the virtual environment.

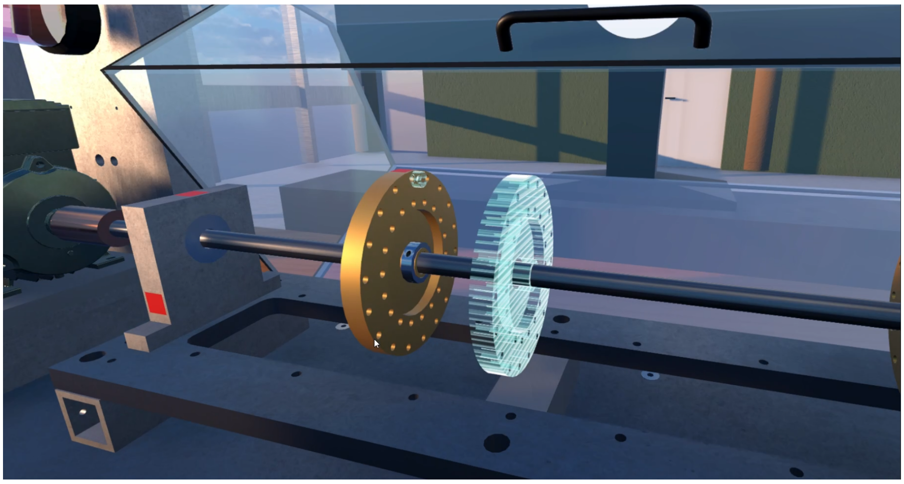


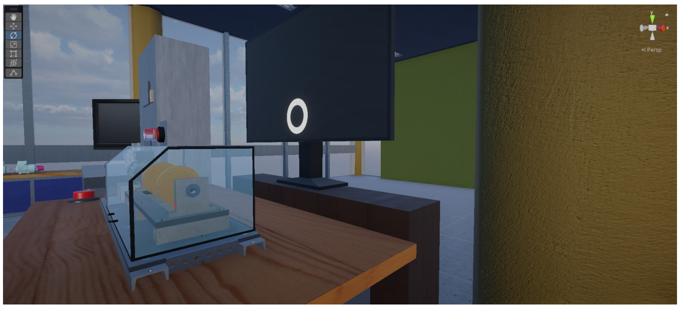
Figure 4.4.: Holograms used as visual cues

4.2. Haptic VR Level

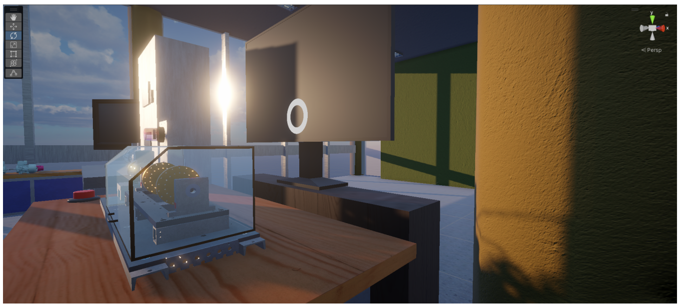
This level of the virtual training tool is an extension on the first level with haptic gloves replacing the controllers. The training tool allows the same set of interactions, only with the input device changed. By leveraging the sensors integrated into the glove, the poses of individual fingers are determined and in turn replicated using a virtual hand within the application. Since the gloves themselves do not have built-in trackers to determine their position, we equip them with additional mounts for attaching Oculus controllers. With the help of the attached controllers, wrist tracking is enabled, completing the full hand tracking experience. To ensure precise determination of finger poses, a calibration process is performed. This calibration process is automatically triggered whenever the training tool is restarted, guaranteeing an accurate representation of the hands within the virtual world.

With the integration of the gloves, the users are able to experience haptic feedback in the form of vibrations and force feedback in addition their use as an input device. By enabling this haptic feedback, the touch of objects within the environment can be simulated for the trainees using the tool. Not only can the users feel the touch of grabbable components such as the MFS-RDS discs, they can also feel the resistance coming from the stationary objects within the environment such as the desk and the machinery foundation.

While this level offers multiple improvements on the base level, its limitations should still be mentioned. One limitation is that this level does not contain the teleport functionality offered on the base version since there are no controllers to be used for such input. Even though the fundamental interactions of the training process are all focused within a stationary region and there is no real need of teleportation, it still represents



(a) Set of unlit scene objects



(b) Set of lit scene objects

Figure 4.5.: Screenshots from the scene with PBR material equipped objects

an improvement to the locomotion by giving the user more freedom when it comes to moving. This limitation can be eliminated by adopting a similar method used in the hand tracking variant. Since we are able to determine the pose of all individual fingers along with the wrist and therefore have physical hand tracking, we can reuse the teleportation methods we utilized for the image based hand tracking interaction. By exploiting the individual sensor values of the fingers we can potentially detect the current gesture of the hand and once again use that for executing the teleport command. Another limitation of this immersion level is that while it successfully replicates the plausible feel of palm-sized, it cannot accurately replicate the tactile sensations associated with very small objects. This limitation becomes particularly relevant during interactions with screws, which are key objects in the training process. To overcome this limitation, one possible approach is to increase the collider size of the small objects. Although this may reduce haptic accuracy to some extent, it still provides an improvement compared to having no haptic feedback at all. Through addressing these limitations with the proposed solutions, this version of the virtual training tool can be further improved with potential enhancement on the feelings of immersion and presence.

4.3. Augmented Virtuality Level

The final level of immersion is constructed by the augmentation of our virtual environment with the real-world objects, specifically the MFS-RDS components. In this version of our virtual training tool, the controllers are completely eliminated, relying solely on hand tracking for user input. Trainees can interact with virtual objects using their hands and experience the physical touch of real-world objects. This is accomplished by tracking relevant parts of the MFS-RDS and other interactable objects in the real world, replicating their poses within the virtual environment.

As previously mentioned in Section 3.2, image sequences captured by Oculus Quest 2 cameras are not exposed to the developers and cannot be accessed. For this reason, we employ an external camera and utilize this for the tracking tasks. In order to attach this camera to our headset, we use a unique custom mount, specifically designed for our setup. The mount allows a stable attachment of Logitech BRIO on the front panel of Oculus Quest 2, while still allowing rotations around two axes. The design itself consists of two separate geometries, which in turn are 3D printed and assembled using a screw and washers. By adjusting this screw and the additional screw to attach the camera on the mount, the rotation of the camera around the two axes can be changed and fixed. The mount itself is attached to the VR headset using the clips on either vertical ends and the original cable of the external camera is plugged in between the mount and the headset by using a 90 degree angle USB-C adapter.

Figure 4.6.: Oculus Quest 2 headset with mounted camera

In order to determine the location of the fixed objects within the environment such as the desk and the MFS-RDS foundation, along with the movable discs of the machine, we utilize a set of ArUco markers. The markers are attached on these real-world objects and their pose is estimated after detection by the external camera during the training process. The calculated poses of the tracked objects are relative to the external camera and are in turn positioned within the virtual environment with respect to the VR rig.

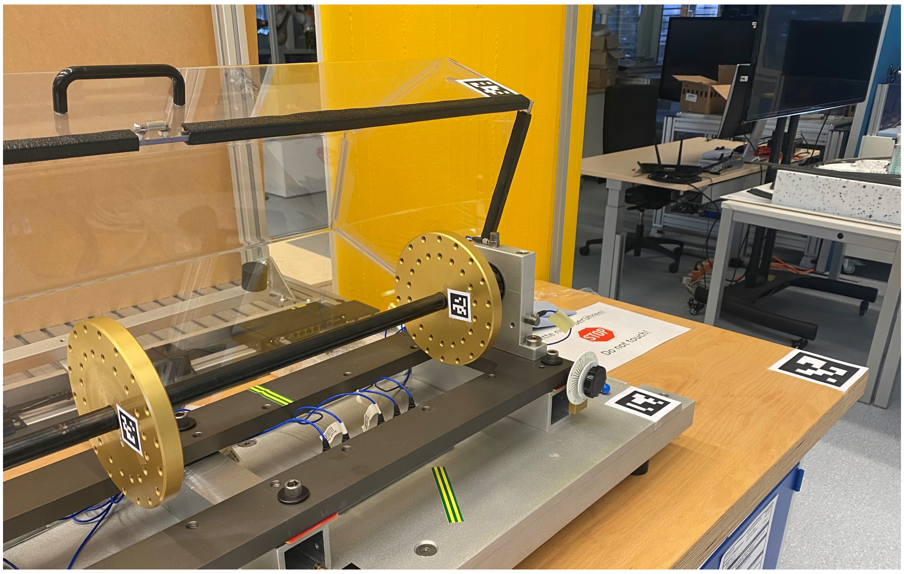


Figure 4.7.: ArUco markers attached on real-world objects

For the purpose of tracking the screws we utilize an additional tracking approach since they are too small to have markers attached. In the first iteration of this level of immersion, we paint the screws in a color that is not present in the scene, such as bright pink or green. By doing so, we are able to color mask the captured frame of the camera and isolate the paint colors within the frame. Following this, color contours are detected and their centers on the screen space are calculated, which represents the position of the screws within the same space. In order to transform the calculated position from the screen space to world space, we send a ray from the VR rig's camera to the world, going through the calculated point on screen. As as intermediary step, a conversion of the screen point coordinate has to be made from the external camera screen space to the VR camera screen space. The point where this ray hits the virtual desk within the scene is regarded as the location for the virtual screw and its position is updated accordingly. As the tracked hands move close enough to to this virtual screw on the table and a pinch is detected, the virtual screw is snapped between the pinching fingers of the virtual hands. Through the indirect tracking of the screw using hand tracking, the interaction with the real-world screw is replicated with limited accuracy. In a later iteration of this immersion level, we make further improvements by painting the screw in two distinct colors, separating its regions. By doing so, we can calculate the two contour centers separately and utilize distance vector between

(a) Frame captured with a painted screw (b) Replicated pose of the virtual screw

Figure 4.8.: Tracking of a screw through a combination of hand-tracking and color masking

to estimate a rotation angle. In turn, this angle is exploited to refine the orientation of the indirectly tracked screw between the pinch fingers, further improving the tracking.

Although we have implemented a working baseline for this immersion level of our tool, it still exhibits some instability and has several limitations and shortcomings. One significant drawback is the tracking of screws on the desk surface. While the location of screws with color contour centers close to middle of the screen can be detected relatively accurately, the estimated positions of the virtual screws deviate significantly from the real screw positions once they are closer to the edges of the camera frame. This issue arises from the use of an external camera for color contour detection, while relying on the VR camera to send rays into the scene. The disparities in pose between the external camera and the VR camera, along with their varying fields of view, prevent a direct and accurate estimation of the object's pose, leading to significant deviations. Additionally, it is important to note that the VR display employs separate cameras for the left and right eye, whereas we only utilize the so called "center eye anchor camera" for our calculation. This introduces additional errors in the pose estimation process. Another limitation of the tool is the jitter of the virtual objects tracked with ArUco markers. Although this limitation has a lesser impact compared to the previous one, it is still worth addressing and improving upon. Additionally, this version of the tool contains a limitation related to the indirect tracking of screws within the hand. In this approach, the virtual screw is positioned at a fixed location between the thumb and index finger, assuming that the user will only hold a real screw in a pinch grip. While this approach is somewhat intuitive, it still presents a limitation as the accurate replication of the screw's position within the hand is compromised when the user holds it differently. While no solutions were formulated to the final limitation with the adoption of our current tracking techniques, potential solutions exist for the former two. The first limitation can potentially be mitigated or even resolved in subsequent iterations by implementing an accurate mapping between the two camera spaces. As for the limitation related to jitter, a combination of methods can be employed. These methods include using a low pass filter, incorporating interpolation of positions from different frames, and reducing the frequency of detected position updates. It is important to note that continuous pose detection for these objects in every frame is not necessary, allowing for further performance improvements.

This version of our tool aimed to create an immersive virtual training process by incorporating augmented virtuality techniques, particularly through the tracking of real-world objects. While the current version of this immersion level has encountered significant limitations, it serves as a valuable prototype that lays the foundation for future development. With further iterations and refinements, we have the opportunity to address these limitations and improve the tool's performance. Drawing from the insights gained through this initial implementation, we can pursue our original design objectives and realize a training experience that enhances both immersion and presence.

5. Evaluation

In this chapter we present an evaluation of our proposed virtual training process. This evaluation is done in the form of a user study and a following analysis of its results. We provide a review of the user study's setting, including the experimental environment and the procedure followed. Subsequently, we present a brief review of the participants' demographics and discuss the questionnaire used in the study, elaborating on its individual sections. Finally, the analysis of the questionnaire responses and the study results are presented, providing valuable insights and uncovering the key findings derived from the evaluation process.

Considering the status of the AV immersion level of our implemented tool, we made a strategic decision to deviate from the initial plan of evaluating all immersion levels independently. Instead, we chose to concentrate our evaluation efforts on the base level of the tool. Although we determined that the current state this version is not suitable for a formal study, we proceeded with a few rounds of informal prototype testing. The objective was to gain initial impressions, gather feedback, and identify any potential areas for improvement that may have been overlooked. These prototype tests aimed to provide an initial understanding of this immersion level's potential and gather insights that can inform future enhancements. This set of test runs led to expected feedback regarding the technical drawbacks of the AV level, aligning with our own deduction of limitations and potential improvements in Section 4.3. Despite these shortcomings, the system still received positive feedback from the prototype testers regarding its inventiveness and potential of increased immersion.

Even though a formal study on the extended immersion levels was not conducted, the evaluation of the base level of the virtual training tool is still valuable for our research. By conducting such a user study and analysing its results, the learning effects of added immersion compared to traditional virtual training processes can still be assessed, along with the overall usability of the implemented training tool.

5.1. Setting

The user study was conducted in multiple different environments with the exact same setup. The change of location was found necessary not only to reach more participants, but also to diversify their background. Since the tested version of the training tool is purely virtual and does not have any dependencies on the real world, the change of real environment in between study sessions had no effect on the results. Before each session, participants were given a brief introduction on the MFS-RDS and its purpose, without sharing any details regarding the operation of the device. The short introduction of the study was followed by the initiation of the implemented tool, in which the users were given a couple minutes of freedom to get adjusted on the basic VR mechanics and the locomotion. Subsequently, the study progressed to the actual run of the training process, consisting of multiple sets of tutorials that cover basic interactions and the **MFS-RDS** balance problem. Upon finishing the tutorials and concluding the trial run, participants were asked to fill out the questionnaire and conclude the session.

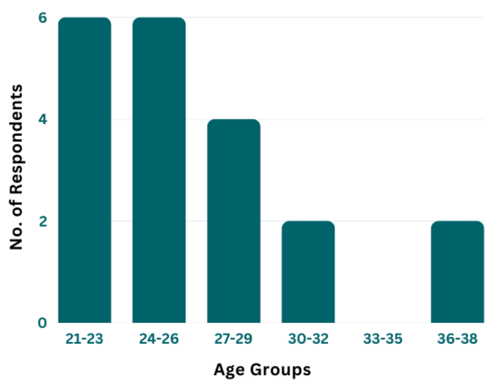
Before we commenced the actual study, a couple test runs were made in order to discover issues that were potentially overlooked. These sessions were did not contain any questionnaires and were not included in the formal study results. Following the test runs, a set of fixes have been implemented such as the resetting of discs and screw positions, along with an improvement on the visual cues of the tutorial. With the implementation of these final adjustments, all significant issues were addressed, resulting in a seamless execution of the virtual training process.

5.2. Participants

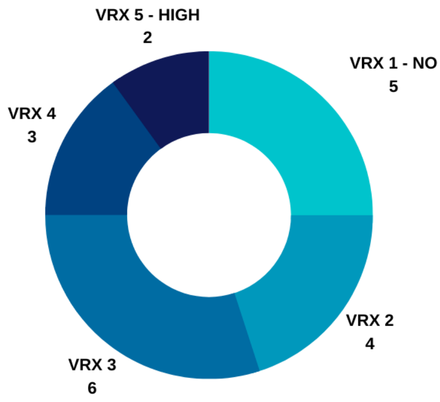
The user study consisted of 20 participants, covering a broad age range from 21 to 38 and creating a diverse and inclusive sample. The participants exhibited varying levels of VR experience, as determined through background questions. They also represented a range of educational backgrounds, including computer science, bioinformatics, mechanical engineering, audio engineering, psychology, and anthropology, which were categorized broadly into informatics, engineering, and social sciences for the analysis of certain results. This diverse group of participants contributes to the richness and breadth of insights gained from the study.

5.3. Questionnaires

In addition to the set of background questions, the questionnaire consisted of four more sections. The first section following the background questions is dedicated for System Usability Scale (SUS), which is a commonly used questionnaire-based tool for assessing the perceived usability of a system. It offers a standardized approach to collect subjective feedback from users, allowing them to express their opinions regarding their experience with the given system. SUS consists of ten statements related to usability, where the users are asked to provide ratings using a Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). In the end, the overall score is calculated which sits in the range of 0 to 100 and represents the perceived usability of the system.



(a) Age distribution



(b) VR experience distribution

Figure 5.1.: Participant demographics

Following the SUS section of the questionnaire, we present another set of five statements which are aimed to determine the participant's opinion on the presented system's potential regarding the learning. Similarly to SUS, the respondents are asked to provide ratings to these five statement with the same Likert scale of one to five. Overall score for this section is calculated by averaging the individual ratings and normalizing this value to the range of 0 to 100. This final score reflects the system's perceived potential on learning.

Nr.	Statement
1.	I can imagine learning new methods with the virtual training tool or any variants of it.
2.	I feel confident in applying the knowledge or skills covered in the training session.
3.	The virtual training tool has the potential to enhance the learning outcome compared to traditional virtual processes (e.g., watching videos or reading manuals).
4.	The virtual training tool is more engaging than traditional learning methods.
5.	The virtual reality training tool is effective in helping me understand and learn new concepts or procedures.

Table 5.1.: Set of learning related statements

The set of learning related statements are followed by a set of questions aimed to test the outcome of the training. They consist of three questions to assess the acquired knowledge during the training process on the unbalance problem of the MFS-RDS. One of the questions contains multiple true/false statements regarding a potential improvement of the balancing while the other two asks the participant to rank given sets of different disc and screw configurations according to their effect on balancing. Moreover, an additional question is asked in order to test the participant's knowledge on safety measures for operating the MFS-RDS, which are presented during the training process.

Finally, the questionnaire concludes with a set of open-ended questions. In addition to determining the aspects of the training that were most valuable and enjoyable to the user, these questions are intended to identify potential improvement that can be done on the system to enhance the learning experience.

5.4. Results

One of the most positive results from the study are the scores we acquired regarding the perceived usability and potential on learning of the tool. Averaging the individual SUS scores, we end up with a value of **85.25**, which indicates a high level of perceived usability among the participants. Furthermore, it is worth mentioning that the system only acquired a single individual score **(67.5)** that is lower than the considered average SUS score of 68 based on research.[1] These results are a strong indication of good usability and suggest that the users found the system efficient, user-friendly and easy to use in general.

Statement Nr.	Average Rating
1.	4.6
2.	4.4
3.	4.6
4.	4.85
5.	4.5

Table 5.2.: Average ratings of individual learning related statements

Additionally, we ended up with an average score of **91.8** regarding the opinion on learning potential. This score is also quite promising and suggests that the participants in general have a positive opinion regarding the potential benefits of the tool on learning outcome. A more detailed analysis shows that among the statements displayed on Table 5.2, statement 2 had the lowest average agreement rating **(4.4)**, whereas statement 4 had the highest **(4.85)**. These specific results suggest that there is more room for improvement regarding the built confidence on applying the acquired knowledge in real-world

[1] J. Sauro. *Measuring Usability with the System Usability Scale (SUS)*. URL: `https://measuringu.com/sus/` (visited on 06/12/2023)

scenarios. This level of confidence can potentially be increased with multiple iterations of the training process and with the first real world application of the learned material. The results also suggest that the users found our tool highly engaging compared to traditional virtual training methods in general. This represent a quite positive outcome, given that one of our main goals designing and implementing this tool was to acquire an increased engagement of the trainee through improvements on the feelings of immersion and presence.

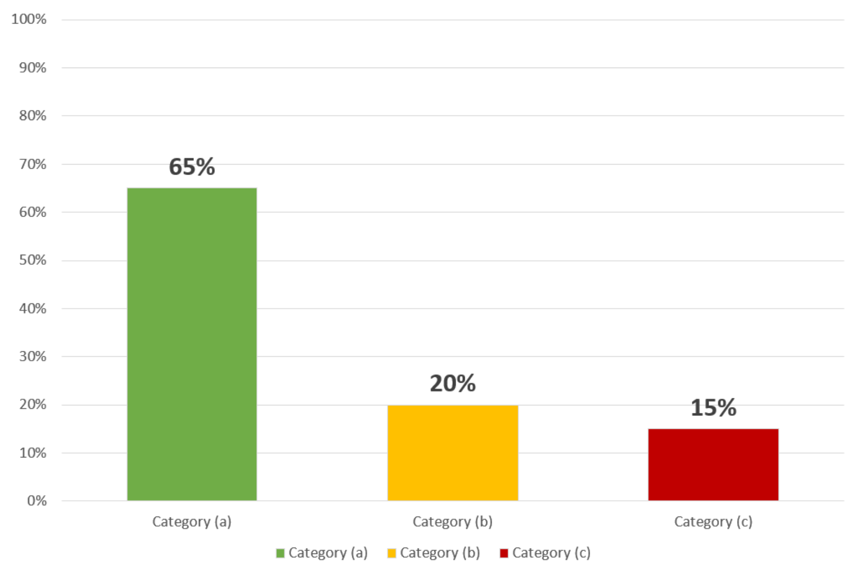


Figure 5.2.: Results for the first question of knowledge test - **(a):** Fully correct responses / **(b):** Partially correct responses / **(c):** Incorrect responses

As seen on Figure 5.2, the results of the first test question can also be interpreted positively. In this question, the respondents were asked to rank a set of possible screw locations on the disc from worst to best, given the optimal screw slot to address the unbalance. While **65%** of the trainees were able to give an exactly correct ranking, a total of **85%** determined at least the worst possible location successfully. The following question had significantly lower success rate in comparison to others. As seen on Figure 5.3, only **25%** of the participants were able to determine the exact set of true statements for the improvement of balance given the optimal slot and a current configuration of the disc. In total, **45%** of the users were able to give at least two correct statement without accepting any of the incorrect statements. As we review the results further, it is seen that **70%** of the users identified at least one correct statements without accepting any incorrect statements, whereas **30%** percent responded with answers containing at least one incorrect statement.

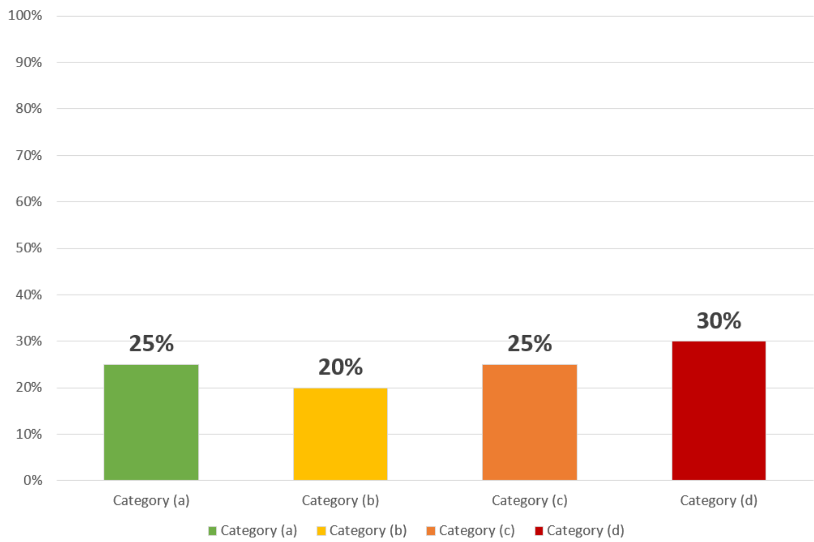
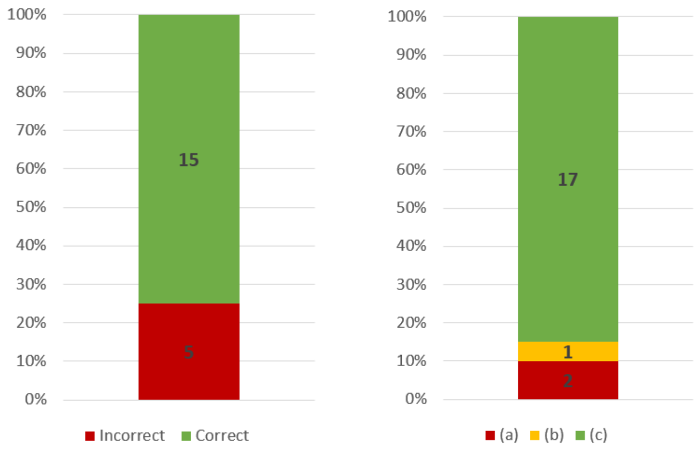


Figure 5.3.: Results for the second question of knowledge test - **(a):** All correct statements w/o any incorrect / **(b):** Two correct statements w/o any incorrect / **(c):** One correct statement w/o any incorrect / **(d):** At least one incorrect statement

The results from the next question aimed at determining the acquired knowledge on optimality of the disc position were significantly positive compared to the previous question. Given a current configuration of a disc, the participants were asked to rank possible disc locations along the shaft from best to worst regarding balance improvement. Among all participants, **75%** were able to successfully give an exact correct ranking of the given disc positions. Finally on a less technical question, **85%** of the trainees were able to identify at least two safety measures for the operation of MFS-RDS, whereas only **10%** were not able to list a single correct safety measure. In addition to the individual analysis of the test question results, we defined an overall scoring of the first three test questions. This overall score is normalized to the range of 0 to 100 similarly to the SUS and the perceived learning potential scores and in turn was utilized for score correlation and background significance analysis.

Although the overall knowledge test scores are not perfect, they are still considered to be above satisfactory, given that the covered unbalance problem lies in a completely foreign field for almost all participants. the scores can be improved with multiple iterations. It is also worth mentioning that a significant portion of the trainees had an educational background completely unrelated to the training scenario. This can have a negative effect on the results regarding the knowledge accuracy and learning outcome, given that they might lack background information such as a fundamental knowledge of physics. This argument is further supported subsequently with an analysis of score distributions across different educational backgrounds and **VR** experience levels.



(a) Question 3

(b) Question 4 - **(a):** Identified no measures / **(b):** Identified only one measure / **(c):** Identified two measures

Figure 5.4.: Results for the third and fourth questions of knowledge test

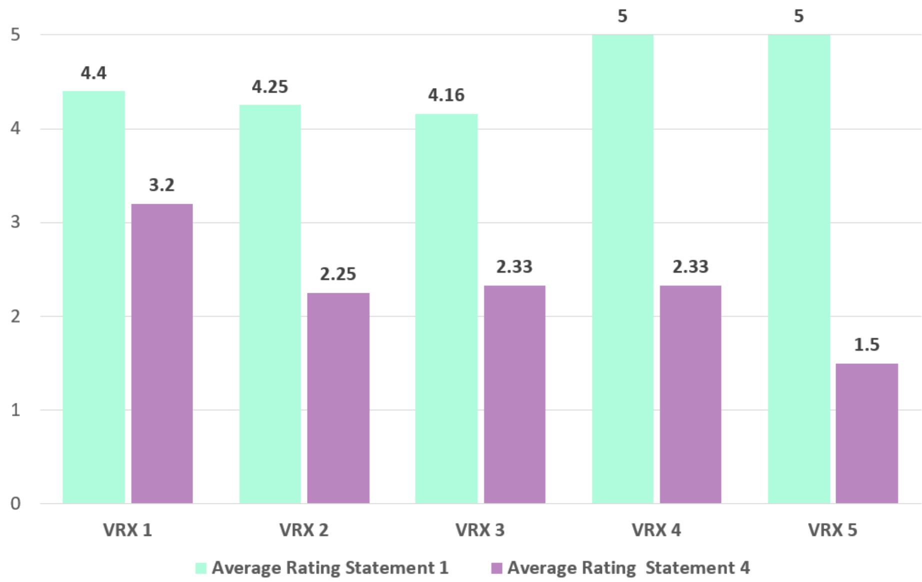


Figure 5.5.: Distribution of average ratings on first and fourth statement of SUS across VR experience groups

With the intention of determining the significance of different background properties, we distributed all of the calculated scores into their corresponding background groups. We utilized the background variables of VR experience and educational background to generate two different distributions and further analysed the results. One result worth mentioning is the distribution of average ratings on the first and fourth statements of SUS as seen on Figure 5.5. The distribution of average ratings across VR experience groups for the first statement depicts a notable difference between the higher experience groups and the lower. This difference suggests a higher system acceptance rate from the users with more VR experience. Furthermore, we observe a significant difference regarding the responses on the fourth statement of SUS between the lowest and highest experience groups. While the top VR experience group exhibits a strong to moderate disagreement with the statement, the bottom group seems to be leaning more on the agreement side. These results show that the experienced VR users require marginal external support, whereas inexperienced users feel less competent without the presence of external support compared to the other group. This distribution might suggest that the potential requirement of external technical support is not necessarily related to the design of the training process itself, but rather to the trainee's adaptation to the fundamental VR interactions.

VRX	AVGS	AVGL	AVGK
1	84	89.6	49.9
2	85.6	93	65.3
3	85.4	88	77.7
4	89.2	97.3	59.2
5	81.3	98	63.7

Table 5.3.: Average scores distributed across **VR Experience (VRX)** groups.
Average SUS Score (AVGS): average perceived usability
Average Learning Score (AVGL): average perceived learning potential
Average Knowledge Score (AVGK): average acquired knowledge accuracy

As seen on Table 5.3, analysis of the average scores distributed across VR experience groups displays a notable trend on the average perceived learning potential score. Despite the inconsistency of the trend with the middle experience level, the average scores of the learning potential opinion are shown to also grow with increasing VR experience. This suggests that more experienced VR users in general have a more positive opinion regarding the tested training tool's potential on the learning outcome. It is also worth noting that the most inexperienced group obtained the lowest average test question score **(49.3)** with a significant difference. One potential explanation to this could be that the less experienced trainees had to pay relatively more attention to learning the fundamental VR interactions compared to other groups and focused more on adopting these interactions rather than the actual training concepts.

Educational Background	AVGS	AVGL	AVGK
Informatics	90	96	71
Engineering	86.1	94.2	68.4
Social Sciences	80	84.7	51.8

Table 5.4.: Average scores distributed across educational background groups.

For the second distribution of average scores, we utilized the educational background of the participants. In order to generate a rational distribution for the analysis, the participants are distributed into broader categories of informatics, engineering and social sciences based on their specific educational background. As seen on Table 5.4, we observe significant differences in the average scores based on educational backgrounds, especially on perceived learning potential scores. In order to support this observation, we performed statistical analyses for the categorial difference of these this type of score. Following the Analysis of Variance (ANOVA) for the score of perceived learning potential on educational backgrounds, we end with the results given on Table 5.5. Given that the resulting *F-value* **(3.88)** is greater than *critical F-value* **(3.59)** and the *p-value* **(0.04)** is lower than the traditional significance of 0.05, we reject the null hypothesis of all population means being equal. Based on this analysis, we determine that there are statistically significant differences in perceived learning potential based on the educational background of the participants.

In addition to the analyses based on the participant background variables, we also examine combinations of scores and variables for potential relationships between them. After completing this analysis, we obtain two significant Pearson correlation coefficients, one between the SUS scores and the perceived learning potential scores, the other one between SUS scores and the knowledge test scores. While the latter displays a moderate positive correlation between two scores with a value of approximately **0.35**, the former coefficient shows a strong positive correlation with an approximate value of **0.51**. These results indicate that as the perceived usability of our system increases, a corresponding improvement will be realized on the perceived potential for learning and the accuracy of acquired knowledge during the training process.

Finally, by reviewing the responses given to the last set of open-end questions, we determine the most valuable aspects of the training process, along with potential improvements according to the users. Based on the feedback we acquired on these questions, we establish that one of the favorite aspects of the tested virtual training process is the interactivity and instant feedback of the system. Many of the respondents stated that the most valuable aspect of the training for them was the fact that they could interact with the system and directly experience the result of their actions. According to the user feedback, the possibility to simulate multiple scenarios without the risk of

SUMMARY				
Groups	*Count*	*Sum*	*Average*	*Variance*
Informatics	5	480	96	8
Engineering	9	848	94.2222	52.4444
Social Sciences	6	508	84.6667	105.067

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	446.311	2	223.156	3.88339	0.04082	3.59153
Within Groups	976.889	17	57.4641			
Total	1423.2	19				

Table 5.5.: ANOVA for perceived learning potential score on educational backgrounds

harming oneself or the machinery gives the trainees more confidence, encourages them to try different interactions and scenarios, in turn accelerating the learning process. By observing and experiencing the working principles first-hand, the users become more aware of the rules to follow and the potential outcome of certain actions. Especially, the simulation of hazardous activity and experiencing its outcome following faulty behaviour helps with learning the correct behaviour according to the participants. Furthermore, the users state that the system is significantly more engaging compared to traditional virtual training methods such as e-learning services or videos. As opposed to the linear nature of watching videos and reading manuals, our virtual training system offers its trainees freedom in many aspects, which seems to be quite well received by the participants of the study. Moreover, we observe a significant portion of the participants reflecting highly positively on the realism aspect of the training process. According to the users, the realistic environment, lighting and sounds were some of the most valuable aspects of the process and helped them feel more immersed. In addition to realism, the visual cues employed to guide the users throughout the training process appears to be well-received and considered significantly helpful with regards to following the instructions.

In addition to the positive feedback the training process has received, we were also able to identify aspects of it that required more improvement. After analysing the user feedback, we discover that the process needs improvements regarding the set of textual guidance given to the trainees. According to a significant portion of the users, the text instructions can be made clearer and simplified. Besides the simplification, the instructions can be enhanced with additional material such as images and videos. This in turn, would allow the tool to transmit more information without the necessity of using long texts. On top of finding the complexity of the instructions, some users state that they require further explanations regarding physics of the unbalance problem. Based on the feedback, we also observe that part of the trainees struggled with some of the interactions, especially the grabbing of smaller objects such as the allen key. These limitations should be addressed on the later iterations of the virtual training tool in order to improve the general user experience, in turn enhancing the learning experience itself.

In summary, the results of the user study show us that our virtual training process is well-received with high perceived usability. We also observe that the trainees in general have a positive opinion towards the training tool's potential on learning and the training process is promising regarding the accuracy of the transmitted knowledge. Furthermore, our analysis shows correlations between the results and the background variables, indicating that the assessments of the proposed virtual training process can be further improved given the correct target groups. Considering the industry orientation of the specific training scenario, it is reasonable to expect an improvement on the learning outcome of the training with more suitable trainee backgrounds. By addressing the limitations of the tool and enhancing the user experience more, the training process can be taken to the next level, potentially further increasing the positive effect on learning.

6. Future Work

In this section, we review potential improvements of our virtual training tool based on our own identifications of limitations and the feedback obtained from the user studies. In addition to addressing of the training tool's limitations, we suggest future work to be done on the proposed virtual training process that can potentially enhance the training outcome. Moreover, we propose additional evaluations which can further contribute to this research.

Based on the limitations we identified during the implementation phase, we review the immersion levels individually for improvements and combine some of them with the feedback from user studies. Starting from the first level, one aspect that needs improvement is the grab mechanics, specifically regarding objects with colliders larger than hand, such as the MFS-RDS discs and the drawer handles. While the interaction with these objects can be performed without any issues on the basic controller based and the hand tracking based interactions, it represents a problem under the use of synthetic hands, which is the adopted way of interaction on the base level. It has been observed that once all of the finger colliders of the synthetic hand are in the convex hull of the large object to be interacted with, the object gets stuck registered as grabbed even when the hand is away from it, in turn making the hand unusable for further interactions. This observation aligns with the feedback we obtained from the user studies, where a significant portion of the participants indicated that the grab interactions require improvement, especially regarding the interactable tools. In order to address these issues, we need to revise the grab mechanics, adjust the colliders of smaller objects so they are easier to interact with and consider implementing an automated detection and resolution of a stuck synthetic hand. Moving on to the second level of immersion, another limitation we identified is the lack of teleport functionality. As previously suggested, such functionality can be realized also for this version with a combination of our hand-tracking teleport implementation and gesture recognition through exploitation of haptic gloves' sensor values. Combining these two approaches, we can further advance the locomotion with the addition of teleportation on this immersion level and improve on general user experience. A further limitation related to grab mechanics was observed within this level, namely the inaccurate haptic feedback on small objects such as screws. As the lack of haptic feedback on these small objects was fixed with an enlargement of the colliders, an inaccuracy between the visual and haptic perception was introduced. While there is no solution to address this problem under the employment of current set of haptic gloves, this limitation can be addressed with the integration of a new set of gloves supporting tactile feedback on finger tips. More novel technologies can be experimented with in order to potentially improve the haptic feedback and combination of them can be employed. One sensible combination is the combination of the two haptic devices we experimented with, namely the SenseGlove and Hapticlabs DevKit. In addition to the current use of haptic gloves, latter device can be integrated into our tool in order to make use of additional haptic feedback, such as simulating the vibration of a loud motor in close proximity with the attachment of the device on user's chest.

Other limitations we identified during and following the implementation phase are specific to the AV version of our tool. On this version, we identified issues including jitter of virtual objects tracked with markers, inaccurate tracking of the screws on the desk surface and limiting the in-hand screw position to pinch fingers' center. While the former two issues can be addressed with adjustments including low-pass filters and interpolation of multiple frame positions on marker tracking, and an improved mapping between the external and VR camera spaces for color mask tracking, a reasonable solution for the latter limitation cannot be realized with the current employment of tracking techniques. In order to address the existing issues with this version of our tool and obtain a stable AV version in general, we propose the integration of other more formal image-based tracking methods. With the current training scenario and the set of allowed interactions, the adoption of learning based tracking methods are also possible in addition to the non-learning based methods, given that the objects that need to be tracked are limited to screws. Following the training of such learning based tracking methods, we can potentially obtain a far improved tracking, that is also robust against partial occlusions unlike our current method. Through this change, the AV immersion level of our proposed tool can actually reach the initial goals we set during the design phase.

In addition to further improvements on the realism aspect of the tool such as equipping it with more props and additional sounds, we also see the potential to improve on the performance. One of the possible future improvements that can have a positive effect on both the realism and the performance is the adoption of Level of Detail (LOD)s. Furthermore, by replacing realtime lighting within the scene with baked lights, we can obtain significantly better performance and improved lighting. By incorporating LODs for more complex objects within the scene and baking the scene after proper light adjustments, we can maintain improved graphics with less adverse effects on the performance.

Before continuing with future work regarding the evaluation, we propose improvements on the guidance through balance problem tutorials of our training process. Based on the feedback we received as part of the user studies, we identify adaptations on the textual guidance that can potentially lead to improved learning results. These changes include simplification of the text content and employing accompanying multimedia elements such as videos and additional images. Moreover, the set of instructions can be split into subsections by further dissecting the tutorial steps, making them more comprehensible and in turn enhancing the learning process and improving its outcome.

Finally, we propose future evaluations to further contribute to the research done on this thesis. In order to obtain an improved analysis on the impact of immersion during the training, we propose a user study testing all individual immersion levels of the proposed tool. After the implementation of fully stable versions, user studies consisting of all immersion levels should be performed to make a comparative analysis. By utilizing multiple immersion levels of the implemented virtual training tool, it will be possible to perform more in-depth analyses that consider the varying levels of immersion. It will also be interesting to extend the time frame of the user studies and perform further evaluations. Some possible subsequent studies can be the evaluation of the results after multiple iterations of the training process on the same individual, and more long term evaluations aimed to determine the success in knowledge retention. Furthermore, the learning outcome of the training process can possibly be measure with more quantitative metrics. As a replacement or in addition to testing the acquired knowledge with questions, real life tasks can be given to the trainee following the process, where the time spent and accuracy of the actions taken can be measured. Through performing these additional evaluations, we can come up with more findings and acquire better insights regarding the impact of immersion and presence during virtual training processes.

7. Conclusion

In this work we presented the design and implementation of a virtual training process aimed to improve on the learning outcome by expanding on the feelings of immersion and presence. We introduced our motivation for the development and evaluation of the proposed virtual training process and presented related work on the concepts related to the scope of our own research.

Subsequently, we reviewed the complete research process, starting from our initial design ideas and motivations. Following, we reported on our experiments aimed to realize our design ideas and presented our first assessments. We reviewed the design changes and adaptations made on the initial ideas in response to the experience and insights collected during the experiment phase, and justified the changes based on our requirements. Furthermore, we gave a detailed introduction of the general structure of the tool and all three versions of it we defined as immersion levels. We presented the hardware and other assets we employed to realize these versions, along with the set of techniques we adopted.

Following the review of the research process and a detailed introduction to our implementation, we presented the evaluation of the implemented virtual training tool. We performed the evaluation review by presenting the user studies we conducted. We further elaborated on the setting of the user studies and the demography of the participants, along with a review of the questionnaires we employed and our motivation for its specific sections. Consequently, we performed an in-depth analysis of the study results, assessed multiple aspects of the proposed tool, and showed correlations between the results and the background variables. As a result of the analysis, we concluded that the presented virtual training process is received highly positively with regards to perceived usability and potential on learning. In addition, we observe that the proposed virtual training process is promising with regards to accuracy in transmitted knowledge and argue that the assessments can be further improved with further iterations and trainees with suitable backgrounds for the specific scenario.

Finally, we discussed future work to address limitations of the implemented tool and to further enhance the overall training process. We presented potential improvements on the proposed virtual training process and introduced additional evaluations that can be valuable to the research. We concluded that the realization of the future work can lead to further advancement on immersion and usability, in turn enhancing the observed strengths of the proposed virtual training process compared to traditional approaches.

A. Immersion Review

Authors	A property of the system	A perceptual response	A response to narratives	A response to challenges
Slater (2003)	***System immersion*: A property of the technology mediating the experience. The higher the fidelity of displays and tracking, the greater the level of immersion.**			
Witmer and Singer (1998)		**Immersion:** A feeling of being enveloped by, included in, & interacting with the virtual environment.		
Arsenault (2005)		**Sensory immersion:** A sensation of being enveloped by the multisensory representation of the virtual world delivered via high-fidelity displays.	**Fictional immersion:** The sensation of being mentally absorbed by fictional stories, worlds or characters.	**Systemic immersion:** The mental absorption experienced when facing challenges that match one's capabilities, including the challenges involved when exposed to nonparticipatory media.
McMahan (2003)		**Perceptual immersion:** The sensation of being surrounded by the virtual environment that increases proportionally with the number of modalities provided with artificial stimuli.	**Psychological immersion (immersion on a diegetic level):** The mental absorption experienced during exposure to the world of a game's story.	**Engagement (immersion on a nondiegetic level):** The state of focused attention on the game brought about by the desire for gaining points and/or devising a winning or spectacular strategy.
Adams and Rollings (2006)			**Narrative immersion:** A state of intense and focused attention on the story world & the unfolding events and acceptance of these as real.	**Strategic and tactical immersion:** A state of intense preoccupation with observation, calculation, & planning or with swift responses to obstacles.
Ermi and Mäyrä (2005)		**Sensory immersion:** The feeling of being surrounded by the multisensory representation of virtual worlds delivered through large screens and powerful sounds.	**Imaginative immersion:** The sensation of being mentally absorbed by a game's story, its world, or its characters.	**Challenge-based immersion:** The mental absorption experienced when facing challenges requiring mental or motor skills.
Ryan (2003; 2008)			**Narrative immersion:** A state of intense focus on a narrative; can be divided into 3 subcategories: *immersion* (elicited by a strong sense of place and the joy of exploration), *temporal immersion* (caused by a desire to know what will happen next), and *emotional immersion* (brought about by emotional attachment to characters).	**Ludic immersion:** A state of intense absorption in the task currently being performed.

Table A.1.: A summary of immersion definitions [NNS16]

B. Education and Training Olfactory Interfaces

Reviewed Research	Olfactory Technology Used in the Research	Experimental/Testing Main Findings
Lai (2015) [63] developed an interactive art exhibition where patrons perceived five odors	Mist diffusers	Odors worked as a powerful communication medium and complemented other senses in the artistic perception
Visitors of London's Tate Gallery held and smelled 3D printed scented objects that were related to some paintings (Vi et al. (2017) [64])	3D printed scented objects	Smells were useful in supporting understanding the paintings' meaning and artistic renderings
Tijou et al. (2006) [65] developed a fully immersive desktop virtual reality (VR) system to investigate the effects of olfaction on learning, recall and retention of 3D structures of organic molecules	Scented gels stored into cartridges and fans	The paper demonstrated the feasibility of a multimodal VR system (including smell) used for learning in the sciences
Richard et al. (2006) [66] introduced the "Nice-smelling Interactive Multimedia Alphabet" project that involved developing a multimodal computer application that included olfactory, visual and auditory information	Scented gels stored into cartridges and fans	No reported research results
Miyaura et al. (2011) [67] developed an olfactory display to help learners re-engage in math tasks	ink-jet technology with scented droplets	The researchers reported that the odors helped to decrease errors in the additions
Kwok et al. (2009) [68] developed and tested a multimodal ambient room for learning with visual, auditory and olfactory stimuli	Olfactory display system with spray dispensers	Preliminary findings of post-tests applied to learners showed that the multimodal ambient room influenced students' affective experiences, improving their learning effectiveness

Table B.1.: A summary of research on educational olfactory interfaces [GKR21]

Reviewed Research	Olfactory Technology Used in the Research	Experimental/Testing Main Findings
Garcia-Ruiz et al. (2008) [69] developed a 3D virtual environment for learning English language	Fresh leaves of mint (Mentha Spicata)	The students perceived the usability of the multimodal virtual environment as very good. In addition, students reported that the mint odor helped students lower their anxiety when listening to the oral instructions in English
Czyzewski et al. (2010) [39] developed a multimodal educational software showing animated cartoons of animals	A device that generated small drops of scented oil, previously stored in a glass pipe, and rapidly released to the environment using compressed air	Initial tests helped to fix technical problems from the device and to analyze the effectiveness of the olfactory device, although their testing results were inconclusive
Covaci et al. (2018) [75] developed a multiplayer serious game intended to teach high-school students about the seventeenth century's Age of Discovery	Small jars containing odors of real spices and beans	Multisensory stimulation in the serious game engaged the users, potentially improving the learning process. However, pre-test and post-test knowledge questionnaire results showed that the olfactory feedback did not yield an improvement in students' performance
Klašnja-Milićević et al. (2018) [84] investigated olfaction-based applications in multimodal VR application for learning the solar system	Essential oil vapors	A within-groups test showed that participants who consumed the chocolate, drank the coffee and smelled the citrus oil vapor while using the VR learning application scored higher in a knowledge pre-/post-test
Alkasasbeh and Ghinea (2019) [85] developed a multimodal website for learning about geography	Dry-air scent diffuser and fans	Results showed that the questions from the post-test in which the olfactory media was synchronized with the audiovisual media was significantly different (improved with higher than average scores) compared to those who were not provided with any olfactory stimuli. However, the odor-only related questions yielded no significant difference

Table B.2.: A summary of research on educational olfactory interfaces *Cont.* [GKR21]

Reviewed Research	Olfactory Technology Used in the Research	Experimental/Testing Main Findings
Cater (1996) [32] developed a virtual reality system for training firefighters,	Wearable olfactory display that generated different types of smoke	Strong smoke caused extreme discomfort in trainees
Spencer (2006) [89] and Kent et al. (2016) [90] conducted literature reviews of research projects that developed and tested medical simulators that incorporated olfactory displays	Various virtual reality technologies	The literature reviews highlighted the feasibility of virtual reality and olfactory displays in medical training, where this technology may support medical diagnoses and benefit training of medicine students
Vlahos (2006) [91] reported that theme park designers and the University of Southern California developed a virtual reality system with an olfactory display for training soldiers	Soldiers don a collar with cartridges that activate wirelessly. The collar has four smell-soaked wicks that send the smells to the trainee's nose with micro fans	Smell improved soldiers' mental immersion in the simulated war scenario, positively supporting training
Tsai and Hsieh (2012) [21] used odors for supporting training of computer programmers for improving coding style and identifying coding errors	Arduino™ microcontroller board connected to a pair of off-the-shelf household aromatizers	More than 80% of participants in a test declared that smells were useful for identifying coding errors
Narciso et al. (2019) [92] developed a virtual reality system with olfactory display for supporting training of firefighters	A commercial olfactory system that diffused smell of burnt wood with compressed air	A between-groups experimental results shown that overall, the multimodal virtual reality system supported knowledge transfer but the experimental group with the smell condition did not significantly improve participants' presence, cybersickness, fatigue, stress and knowledge transfer

Table B.3.: A summary of research on training olfactory interfaces [GKR21]

Abbreviations

VR Virtual Reality

AV Augmented Virtuality

AR Augmented Reality

XR Extended Reality

MR Mixed Reality

RV Reality-Virtuality

MFS-RDS Machinery Fault Simulator - Rotor Dynamics Simulator

BLE Bluetooth Low Energy

SDK Software Development Kit

ERM Eccentric Rotating Mass

VC Voice Coil

LRA Linear Resonant Actuator

RBGT Region-Based Gaussian Tracker

SRT3D Sparse Region-Based 3D Object Tracking

RBOT Region-based Object Tracking

API Application Programming Interface

dFoV Diagonal Field of View

DLL Dynamic-link library

URP Universal Render Pipeline

PBR Physically Based Rendering

SUS System Usability Scale

ANOVA Analysis of Variance

VRX VR Experience

AVGS Average SUS Score

AVGL Average Learning Score

AVGK Average Knowledge Score

LOD Level of Detail

List of Figures

2.1. Simplified representation of a RV Continuum 12
2.2. Basic steps for tracking an object 16
2.3. Applications of digital twins distributed in different lifecycle phases . . . 17

3.1. MFS-RDS with multiple discs attached along the shaft 20
3.2. OVR ION 24
3.3. SenseGlove with an Oculus Quest 2 controller attached for wrist tracking 25
3.4. Hapticlabs satellite connected with an input unit along with an ERM and VC on separate channels 26
3.5. Screenshots from Hapticlabs Studio depicting the preparation of tracks and satellite setup 27
3.6. Levels of Immersion 31
3.7. Level 1 – Basic VR Training Case 32
3.8. Level 2 – Haptics VR Training Case 32
3.9. Level 3 – Augmented Virtuality Training Case 33

4.1. Teleportation with hand tracking 36
4.2. Basic controller based grab interactions 37
4.3. MFS-RDS discs with a single screw attached for balancing 38
4.4. Holograms used as visual cues 39
4.5. Screenshots from the scene with PBR material equipped objects 40
4.6. Oculus Quest 2 headset with mounted camera 41
4.7. ArUco markers attached on real-world objects 42
4.8. Tracking of a screw through a combination of hand-tracking and color masking 43

5.1. Participant demographics 47
5.2. Results for the first question of knowledge test 49
5.3. Results for the second question of knowledge test 50
5.4. Results for the third and fourth questions of knowledge test 51
5.5. Distribution of average ratings on first and fourth statement of SUS across VR experience groups 51

List of Tables

5.1. Set of learning related statements 47
5.2. Average ratings of individual learning related statements 48
5.3. Average scores distributed across VRX groups. 52
5.4. Average scores distributed across educational background groups. 53
5.5. ANOVA for perceived learning potential score on educational backgrounds 54

A.1. A summary of immersion definitions 63

B.1. A summary of research on educational olfactory interfaces 65
B.2. A summary of research on educational olfactory interfaces *Cont.* 66
B.3. A summary of research on training olfactory interfaces 67

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